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Optimization and traction control

Presented and defended by:

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I would like to dedicate this project to my supportive parents who encouraged and inspired me in conducting this study. They have never left my side throughout the process and gave me strength and hope when I thought of giving this up. They provided me a great sense of enthusiasm and perseverance in continuing this. Without their love and assistance, this research would not have been made possible.

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To my friends: thank you for your unwavering support, encouragement, and the countless moments of laughter and inspiration that helped me persevere throughout this journey.

This achievement is as much yours as it is mine.



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Dedication

I want to dedicate this project to my helpful parents who helped and motivated me in doing this study. They have always been with me through everything and gave me power and hope when I thought of stopping. They gave me a strong feeling of excitement and not giving up in keeping going. Without their love and help, this research would not have been possible.

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Abstract:

Switched reluctance motors (SRMs) are prized for their rugged, cost-effective design and lack of permanent magnets, yet inherent torque ripples cause vibrations and acoustic noise, limiting their adoption. This study proposes direct torque control (DTC) to address these challenges by directly regulating electromagnetic torque, bypassing traditional current control loops. Simulations comparing DTC with PI-based methods demonstrate its superiority in minimizing torque pulsations, reducing mechanical stress, and improving operational smoothness. Results highlight DTC's efficacy for electric vehicle propulsion, where noise reduction and energy efficiency are critical. By effectively mitigating torque ripple, this work advances SRMs as sustainable mobility solutions, transforming theoretical robustness into practical performance.

Keywords: (SRM); Switched Reluctance Motor, (DTC); Direct Torque Control, (PI); Proportional Integral, (EV); Electric Vehicles.

Resumé

Les moteurs à réluctance variable (MRV) sont appréciés pour leur conception robuste, économique et l'absence d'aimants permanents, cependant, leurs ondulations de couple intrinsèques provoquent des vibrations et du bruit acoustique, limitant leur adoption. Cette étude propose la commande directe du couple (DTC) pour résoudre ces défis en régulant directement le couple électromagnétique, contournant les boucles de contrôle de courant traditionnelles. Des simulations comparant la DTC aux méthodes basées sur PI démontrent sa supériorité dans la réduction des pulsations de couple, des contraintes mécaniques et l'amélioration de la fluidité opérationnelle. Les résultats soulignent l'efficacité de la DTC pour la propulsion électrique, où la réduction du bruit et l'efficacité énergétique sont cruciales. En atténuant efficacement les ondulations de couple, ce travail positionne les MRV comme des solutions de mobilité durable, transformant leur robustesse théorique en performances pratiques.

Mots clés : (MRV); Machine à Réluctance Variable, (DTC) : Contrôle Direct du Couple, (PI) ; Régulateur Proportionnel Intégrateur, (VE) ; Véhicule électrique.

الملخص

تُعتبر المحركات ذات الممانعة المتغيرة (SRMs) خيارًا مميزًا لتصميمها المتين وفعاليتها التكلفية وعدم احتوائها على مغناطيس دائم، لكن تذبذبات العزم الكامنة فيها تسبب اهتزازات وضوضاءً صوتية، مما يحد من انتشارها. تقدم هذه الدراسة تقنية التحكم المباشر في العزم (DTC)لمواجهة هذه التحديات عبر تنظيم العزم الكهرومغناطيسي مباشرةً، متجاوزةً حلقات التحكم في التيار التقليدية. أظهرت محاكيات مقارنة بين DTC وطرق التحكم القائمة على (PI)تفوق الأولى في تقليل النبضات العزمية، وخفض الإجهاد الميكانيكي، وتحسين سلاسة التشغيل. تؤكد النتائج فعالية DTC في أنظمة الدفع الكهربائي، حيث يُعد خفض الضوضاء وكفاءة الطاقة أمرًا بالغ الأهمية. من خلال التخفيف الفعال لتذبذب العزم، يعزز هذا العمل دور SRMs كحلول مستدامة للتنقل، محولًا متانتها النظرية إلى أداء عملي ملموس.

الكلمات المفتاحية: محرك التردد المتغير (MRV)؛ التحكم المباشر في عزم الدوران (DTC)؛ المتحكم التناسبي التكاملي (PI)؛ السيارة كهربائية (EV).

Nomenclature

R	Stator phase resistance
K	Torque and electromotive force coefficients
Ns	Stator teeth
Nr	Rotor teeth
W	Speed
T	Period
We, Wc	Electromagnetic Energy and Co-energy
F	Rotational Frequency
Ω	Angular Velocity of Rotation
J	Rotor Moment of Inertia
F	Coefficient of Friction
TL / Cem	Load Torque
Θ on	Firing Angle
Θ off	Locking Angle
V	Voltage
I	Current
Te	Electromagnetic Torque
ω	Rotation speed
θ	Angular Position of the Rotor compared to the Stator
L	Phase Inductance
$\boldsymbol{\omega}$	Natural Angular Frequency
ξ	Damping Coefficient
R	Magnetic Reluctance
dl	Elementary Length
μ	Magnetic Permeability of the Material
Φ	Magnetic Flux
Φs	Stator flux
Wm	Mechanical Power
Wf	Magnetic Field Energy

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General Introduction

The electric vehicle, known since 1890, was used up until the 1930s, after which the internal combustion engine vehicle became dominant due to its range and cost. Since 1980, the number of polluting thermal vehicles has increased significantly. Alternative solutions have always been considered for urban areas in large cities.Automotive, battery, and electric motor manufacturers are currently pooling their research efforts to meet the requirements set by the various environmental agencies of the European community states.

The electric solution doubly meets the demands of urban mobility, thanks to its absence of gaseous pollution and noise nuisance. The development of electric vehicle projects can be explained first and foremost by the environmental objectives set within global frameworks to combat climate change, specifically aiming to reduce CO_2 emissions. Furthermore, the automotive industry of this era is facing a global crisis and is in need of renewal. The electric car thus appears as a lever for recovery and modernization. Finally, the technological maturity of the lithium-ion battery opens up prospects for the large-scale development of electric vehicles. Until now, the main obstacle to the development of electric vehicles was the battery, whose capacity was insufficient.

This work consists of the modeling, control, regulation, and simulation of a switched reluctance motor in order to better utilize it as the drive motor of choice for electric vehicles. The work is divided into three chapters:

The first chapter is devoted to generalities on electric vehicles. We will begin with a state-of-the-art review and discuss the different architectures, as well as explain their operation.Inthe second chapter, we will present basic concepts about switched reluctance machines. We will also highlight the optimization of switched reluctance machine (SRM) control, which is now a current research topic.In the third chapter, we will propose solutions to the problem of torque ripple, which is practically considered the only significant disadvantage of SRMs and a barrier to making them the motor of first choice despite their numerous advantages that elevate them among the most sought-after motor categories. Regulation by a simple PI controller will not take us very far; for this reason, we will propose direct torque control (DTC) for the 6/4 SRM, which seems to be well suited. In this chapter, we will present the control, regulation, and simulation of the 6/4 SRM in the Matlab/Simulink environment, first using a simple PI controller and then employing DTC. A final comparison between these two approaches will be presented and analysed.We will conclude this work with a general summary that recaps the essential points of this work.

First Chapter

THE ELECTRIC VEHICLE

I.1 Introduction

Nowadays, more than one billion vehicles are on the road, and manufacturers produce over than 80 million new cars each year. Most of these vehicles are powered by internal combustion engines (ICEs) based and relied on conventional energy sources, emitting burned gazes like oxide and dioxide carbon and other pollutants into the atmosphere shows bellow. This contributes to environmental degradation, green house effect and increases significant risks to human being health. It is therefore crucial for the research community to focus on developing clean, sustainable, and green energy sources. However, researchers must advocate for policymakers and economic decision-makers to take concrete actions to address this pressing issue and promote the energy transition. In this context, automotive manufacturers should play a key role in this strategy by investing in research and development to create new prototypes of hybrid and fully electric vehicles.

Gasoline: Incomplete combustion of gasoline can produce compounds such as carbon monoxide (CO), nitrogen oxides (NOx), volatile organic hydrocarbons (VOCs), and particulate matter (PM), in addition to carbon dioxide (CO_2) and water vapor (H_2O). Example of an incomplete combustion equation for gasoline:

$$\mathbf{C_8H_{18}+O_2 \rightarrow CO_2+CO+NOx+VOCs+PM+H_2O}$$

Diesel or gasoil: the same undesirable compounds can be formed during incomplete combustion, such as carbon monoxide (CO), nitrogen oxides (NOx), volatile organic hydrocarbons (VOCs), and particulate matter (PM), in addition to carbon dioxide (CO_2) and water steam (H_2O). Example of an incomplete combustion equation for diesel:

$$\mathbf{C_{12}H_{23}+O_2 \rightarrow CO_2+CO+NOx+VOCs+PM+H_2O}$$

Aircraft fuel (Kerosene): Similarly, various compounds can form during incomplete combustion of the aircraft fuel, such as carbon monoxide (CO), nitrogen oxides (NOx), volatile organic hydrocarbons (VOCs), and particulate matter (PM), in addition to carbon dioxide (CO_2) and water vapor (H_2O). Example of an incomplete combustion equation for aircraft fuel:

$$\mathbf{C_{12}H_{26}+O_2 \rightarrow CO_2+CO+NOx+VOCs+PM+H_2O}$$

We believe that pollution caused by ships and maritime transport exceeds any fears that one might imagine.

Since June 2015, sales of electric vehicles have increased to 49%. The widespread adoption of electric cars worldwide has significantly improved air quality in densely populated areas, reducing the effects of air pollution and mitigating global climate change. To achieve cleaner and greener mobility in highly urbanized cities, electric vehicles must be considered as an unavoidable solution. This "zero-emission" solution relies on a powertrain system consisting of an electric motor and an energy source (battery). Therefore, advancing these concepts will enhance the performance of electric vehicles, and any imbalance in prioritizing one concept over another could negatively influence the vehicle's overall efficiency [1].

I.2- Art state and Electric Vehicles evolution

Mechanic Thomas Davenport in Brandon, United Kingdom built the first electric vehicle, in 1834. He constructed a battery to power an electric motor and used it to drive a small vehicle that successfully made a short trip on rails. In 1859, the secondary lead-acid rechargeable battery was invented by the Frenchman G. Plante [2], and in 1869, Gramme constructed the first direct current (DC) electric motor with a power output of more than one horsepower. Twelve years later, in 1881, the Frenchman Gustave built an electric vehicle equipped with a DC motor powered by lead-acid batteries, with the entire vehicle and its driver weighing about 160 kg [3].

Two years later, two British professors built a similar vehicle. These early achievements did not attract much public attention, as the technology was not mature enough to compete with horse-drawn carriages. Speeds of 15 km/h and a range of 16 km did not excite potential customers.

The following 20 years were a period during which electric vehicles competed with their gasoline counterparts. This was particularly true in America, where there were not many paved roads outside of a few cities [4]. The limited range of electric vehicles was not an issue. However, in Europe, the rapidly growing number of paved roads required longer ranges, favoring gasoline vehicles.

In 1894, Morris and Electroboat by Salom, as illustrated in Figure 1.1 manufactured the first commercial electric vehicle. Its inventors' company operated this vehicle as a taxi in New York. The Electroboat turned out to be more cost-effective than horse-drawn cabs, despite its higher purchase price (about $3000 compared to $1200 at the time). It could be used for three-

quarters of a 4-hour work shift with 90-minute recharge periods between runs. Two horsepower motors powered it, allowing a maximum speed of 32 km/h and a range of 40 km.



FIG I-1:Morris and Salom in the 1894 Electrobat

The most significant technical advancement of this period was the invention of regenerative braking by the Frenchman M.A. Darrac in 1897. This method allows the recovery of kinetic energy from the vehicle during braking, which is then used to recharge the batteries, significantly improving range. It is one of the most important contributions to electric and hybrid vehicle technology, as it enhances energy efficiency more than any other feature in urban driving.

Additionally, one of the most important electric vehicles of this period was the first to reach a speed of 100 km/h. This was "La Jamaiscontente" (Figure 1.2), built by the Frenchman Camille Jenatzy in 1899 [5].

After this period, Electric vehicles began to disappear, with not only their high cost not helping, but also their limited range and performances that hindered them, especially compared to gasoline counterparts that became more powerful and flexible. The last commercially viable electric vehicles were sold around 1905 [6]. For nearly 60 years, the only electric vehicles sold were golf carts and delivery vehicles.

In 1945, the invention of semiconductors like the diodes, transistors and thyristors allowed high switched currents at high voltages. This made it possible to regulate the power supplied to an electric motor without the very inefficient rheostats, and allowed the operation of control.



FIG 1-2: La jamais contente

1980s, environmental concerns spurred some research into electric vehicles and many car manufacturers produced prototypes and small series of electric vehicles designed for specific markets [7]. However, despite advances in battery technology and power electronics, their range and performance remained obstacles. The era of modern electric vehicles peaked in the 1980s and early 1990s with the release of some realistic vehicles by companies such as General Motors. While these vehicles represented a significant success, especially compared to earlier models, it became clear by the early 1990s that electric cars could never compete with gasoline vehicles in terms of range and performances. The reason resides in the batteries. Energy is stored in the metal of the electrodes, which weigh much more than gasoline for the same energy content. The automotive industry abandoned electric vehicles to focus on hybrid electric vehicles. After several years of development, hybrids became much closer to mass production than electric vehicles.

In recent years (starting around 2000), the prototype replacing part of the battery with a fuel cell generator shifted research toward advanced vehicle technologies, focusing on energy management of hybrid sources for electric vehicles, as well as fuel cells, super-capacitors, or batteries [8] Hybridizing the fuel cell system with a high-end power source is an effective technology to overcome the disadvantages of vehicles that run solely on fuel cells.

In the development of electric vehicles, battery technology remains the weakest link, blocking the electric vehicle market. Significant efforts and investments have been made in battery research to improve performance to meet the needs of electric vehicles. Unfortunately, progress has been very limited. Performance lags far behind the needs, particularly in terms of energy storage capacity per unit of weight and volume. This limited energy storage capacity of

batteries restricts electric vehicles to certain applications, such as airports, rail-road stations, mail distribution routes, golf courses, etc. In fact, a basic study shows that electric vehicles could compete with liquid-fueled vehicles, even with the optimistic value of battery energy capacity. However, the automo tive industry has been an important driver of research because electric vehicles are now considered the vehicles of the future and a possible solution to reduce greenhouse gas emissions in the environment. Today, all major car manufacturers produce electric vehicles. Many of them are available for sale or in public locations. Numerous prototypes such as the Toyota PRIUS, Nissan MIEV, Peugeot, and hydrogen fuel cell electric London taxis are currently available (These electric vehicles contain induction motors, permanent magnet synchronous motors) [9].



FIG 1.3: Global Sales of Electric Vehicles

I.3- Electric Vehicles definition (EV)

An electric vehicle (EV) is a mode of transportation powered by one or more electric motors, which derive their energy mainly or entirely from rechargeable batteries or other forms of electrical energy storage systems. Unlike traditional vehicles that rely on internal combustion engines (ICE) fueled by gasoline or diesel, EVs operate on electricity, making them more environmentally friendly and energy-efficient [9][10].

I.4- Powertrain of Electric Vehicles

The powertrain of an electric vehicle (EV) is the system responsible for converting electrical energy stored in the battery into mechanical energy to propel the vehicle. At its core is the high-voltage battery, which stores energy and powers the electric motor. These batteries, often lithium-ion or lithium-polymer, operate at voltages ranging from 300 V to 800 V, providing the energy needed for driving and onboard systems. The battery's capacity determines the vehicle's range, while its power output affects acceleration and charging speed, making it a critical component of the EV. Emerging technologies like solid-state batteries promise even greater energy density and faster charging times in the future.

The electric motor is the component that converts electrical energy into mechanical energy. Most EVs use alternating current (AC) motors, which are highly efficient (up to 95%) and deliver instant torque, enabling smooth and rapid acceleration. Unlike traditional internal combustion engines, EVs do not require a multi-speed transmission, as the electric motor can operate efficiently across a wide range of speeds. An inverter plays a key role in managing energy flow, converting direct current (DC) from the battery into alternating current (AC) for the motor and regulating power output based on driver input. This ensures optimal performance and energy efficiency.

EVs typically use a single-speed reduction gear to transfer power from the motor to the wheels, simplifying the transmission system and reducing maintenance needs. Differentials are used to distribute power between the wheels, ensuring smooth and stable driving dynamics. The charging system allows the battery to be recharged from external sources, with options for slow charging (AC) at home or public stations (3.7 kW to 22 kW) and fast charging (DC) at dedicated stations (50 kW to 350 kW). Fast charging significantly reduces charging times, making EVs more practical for long-distance travel.

A Battery Management System (BMS) monitors and protects the battery, ensuring safety and longevity. It balances the charge across battery cells, prevents overcharging or deep discharging, and monitors temperature and voltage. Regenerative braking is another key feature, allowing the vehicle to recover energy during braking or deceleration. The electric motor acts as a generator, converting kinetic energy into electrical energy, which is stored back in the battery. This not only increases the vehicle's range but also reduces wear on the mechanical braking system.

Thermal management systems, often liquid-based, keep critical components like the battery, motor, and inverter at optimal temperatures. Proper cooling ensures safety, reliability, and consistent performance, especially during demanding driving conditions. Together, these components create an efficient, low-maintenance powertrain that reduces emissions and supports sustainable mobility. EVs represent a key shift toward cleaner transportation, driven by advancements in energy storage, motor technology, and power electronics [2][3][4][5].

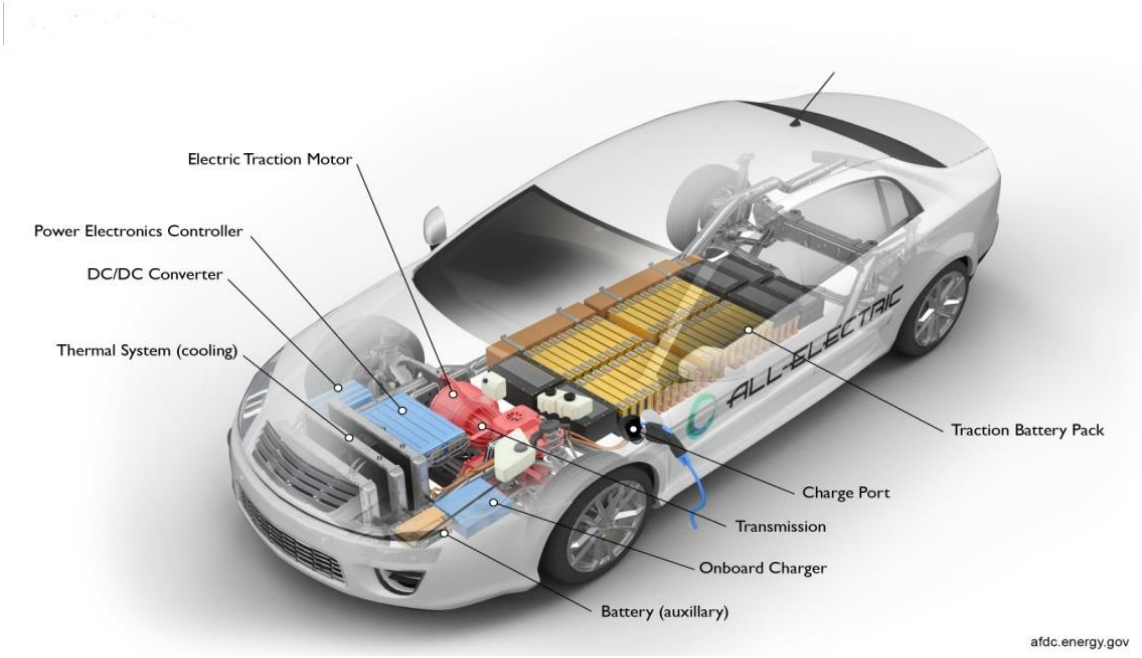


FIG I-3: Elements constituting an electric vehicle

I.5- Operating principal of Electric vehicle

The primary components of an electric vehicle (EV) are illustrated in Figure 1.5. These essential elements include a high-capacity battery for storing electrical energy, one or more traction motors that convert this energy into mechanical motion to drive the vehicle, an energy management computer that optimizes power distribution and efficiency, and a conversion system equipped with a plug for recharging the battery. Together, these components form the core of an EV's powertrain, enabling it to operate efficiently and sustainably.

Charging an electric vehicle is a straightforward process that typically takes place at home in a garage or at the workplace after the driver has completed their journey. In most cases, charging is done using a standard 120V outlet, which provides a slow but convenient way to replenish the battery. For a small-sized EV, this type of charging can take approximately 8 hours to fully recharge the battery. However, many EV owners prefer faster charging options, which are available at public charging stations or dedicated fast-charging points. These fast-

charging systems can significantly reduce charging times, making them ideal for longer trips or when time is limited.

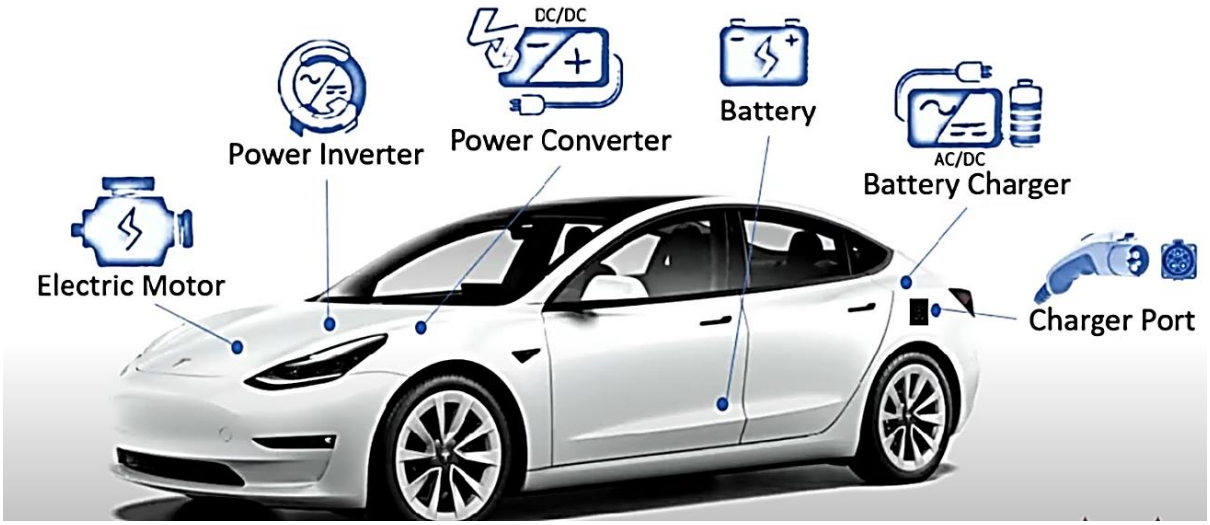


FIG I-4: Components of an EV.

Despite the availability of fast-charging solutions, the fundamental principle of using an electric vehicle remains centered around the idea of recharging during natural stops, such as at home overnight or during work hours. This approach aligns with the typical usage patterns of most drivers, ensuring that the vehicle is always ready for the next trip. The concept of "I recharge when I stop" highlights the convenience and practicality of EVs, as they can be charged during periods when the vehicle is not in use, minimizing downtime and maximizing efficiency [11].

I.6- Classification of Electric vehicles

Advances in power electronics and related technologies have spurred the exploration of new ideas and designs for electric vehicles (EVs), all aimed at improving this mode of propulsion. These innovations revolve around a central challenge: the production, distribution, storage, and utilization of electricity. Electric vehicles fall under the broader category of electrified vehicles, which includes both plug-in hybrids and fully electric models. Within this category, several subcategories exist [12].

I.6.1- Fully Electric vehicles

With an electric motor and a battery that is recharged from the electrical grid, the Fully electric vehicles produce no greenhouse gas (GHG) emissions during operation. Modern fully electric vehicles offer a range that comfortably meets the demands of urban commuting.

Examples of models

- Chevrolet Bolt EV
- Hyundai Kona EV
- Nissan Leaf

There are two main types of fully electric vehicles: those powered by rechargeable batteries and those powered by hydrogen fuel cells[13]

I.6.2- Battery Electric Vehicles (BEVs)

Battery electric vehicles, which rely on rechargeable batteries, dominate the global electric vehicle market. The battery serves as an onboard energy storage system, storing electricity for later use. This technology, first developed in the 19th century, remains the most widely adopted and technically refined energy storage solution for electric vehicles [14].

I.6.3- Fuel Cell Electric Vehicles (FCEVs)

Fuel cell electric vehicles use hydrogen fuel cells to generate electricity. Inside the fuel cell, hydrogen from the tank reacts with oxygen from the air to produce electricity, powering the motor. The only by product of this reaction is water vapor, making FCEVs an environmentally friendly alternative to traditional vehicles [15].

The chemical reaction can be summarized as follows:

$$H_2 + ½\ O_2 \rightarrow H_2O + \text{Electricity} + \text{Heat}$$

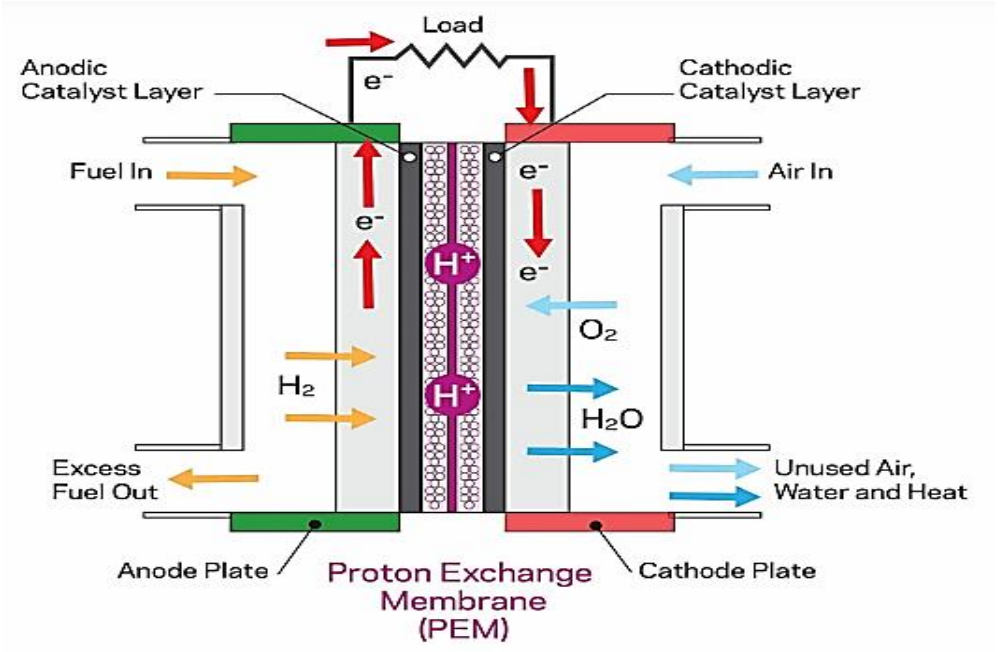


FIG I-5: Operating Principle of a Fuel Cell

I.6.4- Hybrid Vehicles

Hybrid vehicles combine a thermal engine with an electric motor and feature two energy storage systems: a fuel tank and a battery. This dual-powertrain setup allows for optimized energy management, enabling the vehicle to switch between thermal, electric, or combined modes based on driving conditions. By using the thermal engine only in its most efficient range, hybrid vehicles reduce local emissions and fuel consumption by 10 to 50%, depending on the level of hybridization [16].

A- Series Hybrid Vehicles

In a series hybrid, the electric motor is powered by electricity generated by an alternator driven by a thermal engine operating at a constant speed. The two engines are connected in series, hence the name. This setup allows the thermal engine to run at its most efficient speed, reducing emissions and improving fuel economy. The battery acts as a buffer, providing additional power when needed or enabling all-electric operation. However, the overall efficiency of this system is lower due to multiple energy conversions (mechanical to electrical and back to mechanical). Despite this, the architecture offers flexibility in controlling the thermal engine's speed and torque independently of driving conditions. A schematic of this system is shown in Figure 1-7[17].

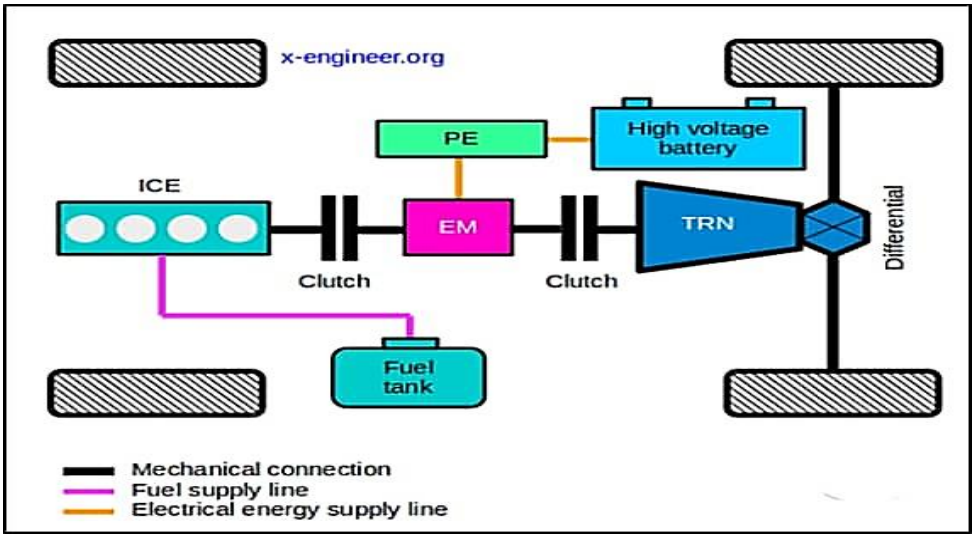


FIG I-6: series hybrid vehicle principle

B- Parallel Hybrid Vehicles

Parallel hybrid vehicles feature both an electric motor and a thermal engine that operate independently or together. This design combines the benefits of both systems: the electric motor handles urban driving with zero emissions, while the thermal engine provides extended range for long-distance travel. This dual-mode operation addresses the limitations of purely electric vehicles while reducing the environmental impact of traditional combustion engines [18].

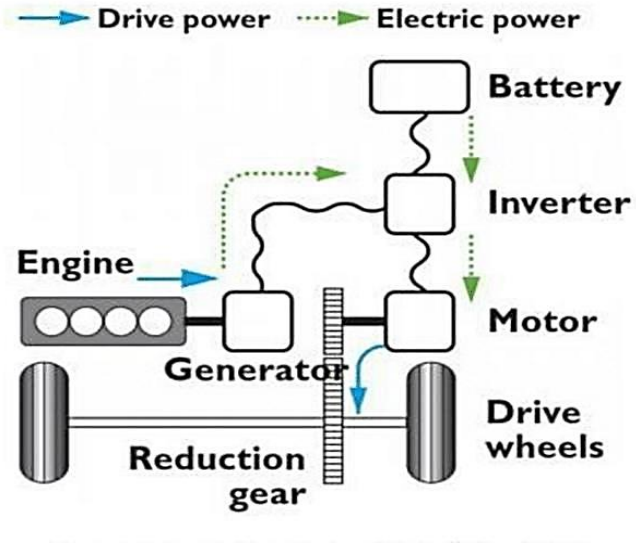


FIG I-7: parallel hybrid vehicle principle

C- Combined Hybrid Vehicles

Combined hybrid vehicles, also known as power-split hybrids, integrate an electric motor, a generator, and a thermal engine. This architecture allows for efficient power management, enabling the thermal engine to operate at optimal speeds while sharing its torque between driving the vehicle and charging the battery. A schematic of this system is shown in [19].

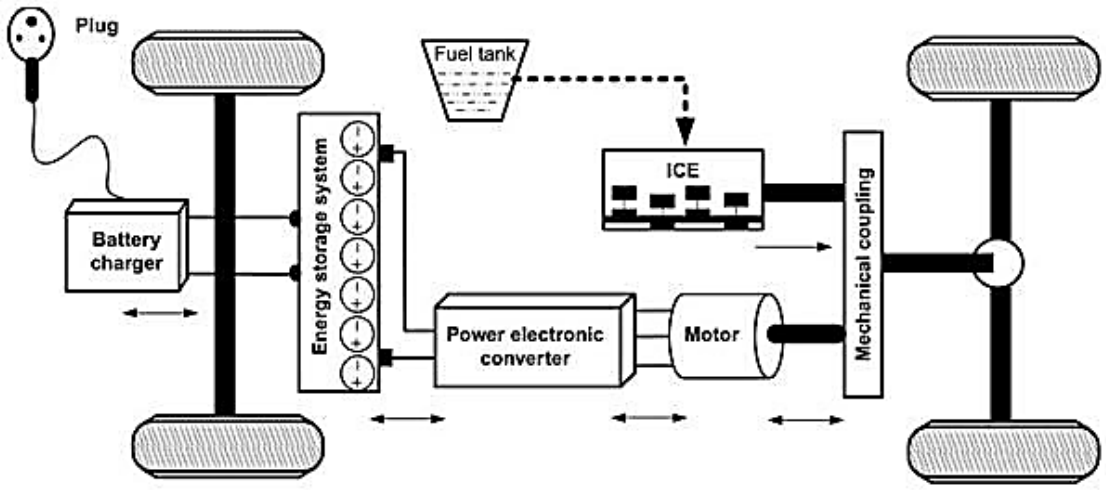


FIG I-8: combined hybrid vehicle principle.

I.7- Power electronics in Electric Vehicles

A. Rectifiers AC/DC

Rectifiers are electronic devices used to convert alternating current (AC) voltage into current (DC) voltage. In many home and commercial applications where a direct current power source is needed, this conversion is crucial. In order to regulate the output voltage and power, power components are essential. Two primary types are noted among these components:

B. Diodes

- Diodes are semiconductor parts that only permit one direction of current flow, from the anode to the cathode. They are employed in uncontrolled rectifiers, which convert AC to DC without allowing for output voltage regulation.

- Diode rectifiers are straightforward and durable, but once the circuit is set up, they do not permit output voltage adjustment.

C. Silicon-Controlled Rectifiers, or thyristors

Compared to diodes, thyristors are more intricate semiconductor parts. They modify the firing angle, or the point at which the thyristor begins conducting, in addition to rectifying current (AC-DC conversion) and controlling the output voltage and power. Thyristors are employed in controlled rectifiers, which allow the output voltage to be adjusted to suit the

needs of the application. This is especially helpful in systems that require precise voltage regulation, like switching power supply or motor speed drives. Their applications are used for:

- **Uncontrolled Rectifiers (Diodes):** Used in straightforward battery chargers and other applications where voltage regulation is not necessary.
- **Controlled Rectifiers (Thyristors):** Found in more intricate applications including power converters, electric traction systems, and industrial power supply that need exact control over voltage and power. In conclusion, the two primary parts of AC-DC rectifiers are thyristors and diodes. For simpler applications, diodes are straightforward and effective, while thyristors offer exact voltage and power control, which makes them essential in more complex systems.[20]

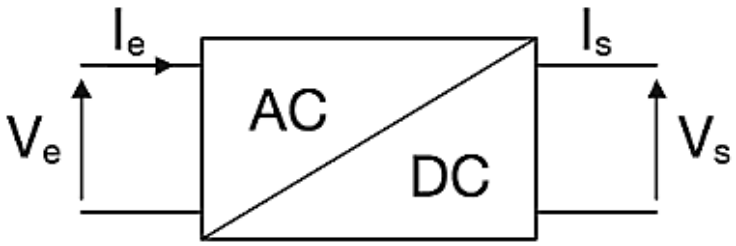


FIG I-9: Rectifier symbol.

D. Choppers (Hacheurs) DC/DC

Static converters known as choppers enable the production of a changing DC voltage with an efficiency that is nearly equal to unity. In alternating current (AC) systems, their function is comparable to that of transformers. Their main applications are in DC switching power supplies and DC motor speed control. These converters make it possible to regulate the flow of energy between a source and a load, which can be either an inductive (current source) or capacitive (voltage source).

-When propulsion motors are DC motors, they are crucial for powering them.
-The main battery's voltage must be adjusted to match that of the electronic auxiliaries (sensors, regulators, etc.) [21].

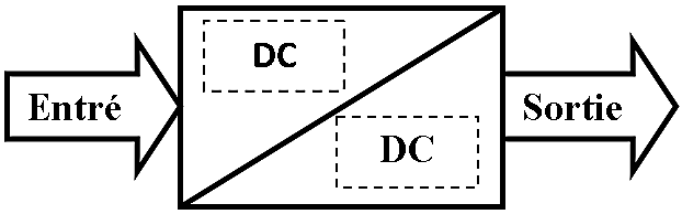


FIG I-10: Choppers Symbol**.**

E. Inverters (Onduleurs)

A power electronics device known as an inverter produces alternating voltages and currents from electrical energy sources that are either direct current (DC) or have a different frequency. It carries out a rectifier's opposite function. An example of a DC/AC static converter is the inverter. The foundation of inverters is an H-bridge structure, which is usually made up of electronic switches like thyristors, power transistors, or IGBTs. The source is modulated to generate an alternating signal with the desired frequency by means of a sequence of carefully regulated switching operations (pulse width modulation).

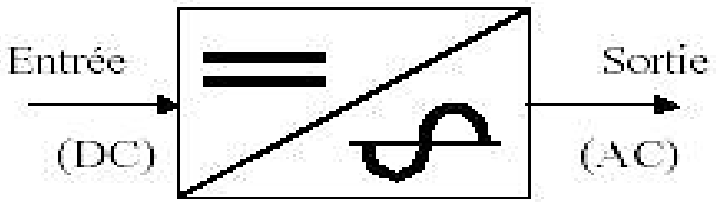


FIG I-11: Inverters Symbol.

I.8 Different traction architecture in Electric Vehicles

For electric vehicle traction, three primary categories of electrical machines are available: direct current machines (MCC), asynchronous machines (MAS), and synchronous machines (MS). The main difference between these machines lies in the power supply type and the converter used. By referring to existing comparisons in the literature, it is possible to clearly identify the advantages and disadvantages of each architecture in terms of their application in the automotive sector.

Table I.1- Examples of the Application of Different Motors in Electric Vehicles

EV Models	**Motorization Types**
Fiat Panda Elettra	MCC Series
Mazda Bongo	Separate MCC
Conceptor G-Van	Separately excited MCC
Suzuki senior	AM MCC
GM EV1	Asynchronous Motor
Toyota Prius	MSAP (Synchronous Permanent Magnet

Chloride Lucas	RV Motor (Reversible Motor)

I.8.1 Single Motor Electric Vehicles

Among the different types of DC motors (series motor, separately excited motor, permanent magnet motor), the separately excited motor is commonly used. It is the most cost-effective and durable option due to the simplicity of controlling DC motors.

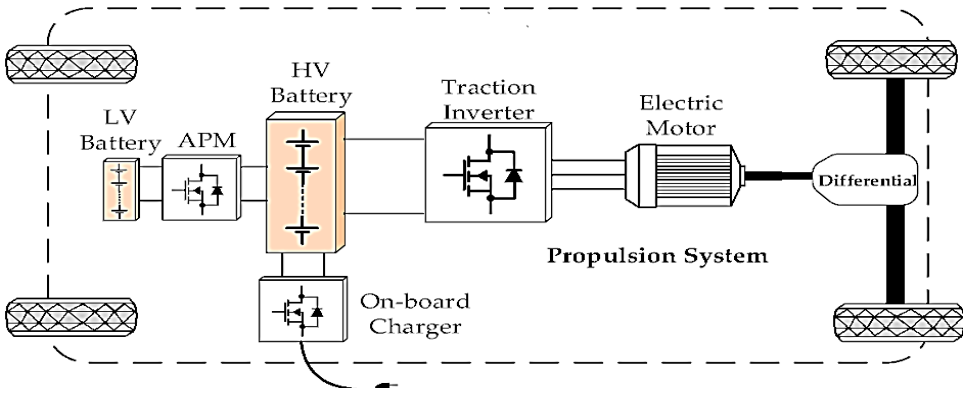


FIG I-12: Architecture of a Single-Motor Electric Vehicle

The first widely produced electric vehicles starting in 1995, such as the Peugeot 106 and Partner, Citroën AX, Saxo, and Berlingo, were equipped with separately excited DC motors. These vehicles were powered by a separately excited DC motor, with nominal and peak powers of 11 kW and 20 kW, respectively, in the case of the 106. The maximum range of their nickel/cadmium batteries was 90 km. While these motors are appealing because of their ease of handling and control, they have a significant disadvantage: they require regular maintenance of the brush-commutator system and offer limited performance. In contrast, alternating current motors, like asynchronous motors, are more efficient for automotive applications.

Table I.2- Advantages and disadvantages of DCM.

Strengths of the DCM	**Weaknesses of the DCM**
-Simple defluxing to perform for the DCM with separate excitation. - Simple speed control.	-The presence of the commutator and brushes system requires regular maintenance. -The torque and mass force make cooling difficult. -High manufacturing cost, mechanically complex machine.

I.8.2 Two-Motor Electric Vehicles

There are two types of alternating current machines: the synchronous motor and the asynchronous motor.

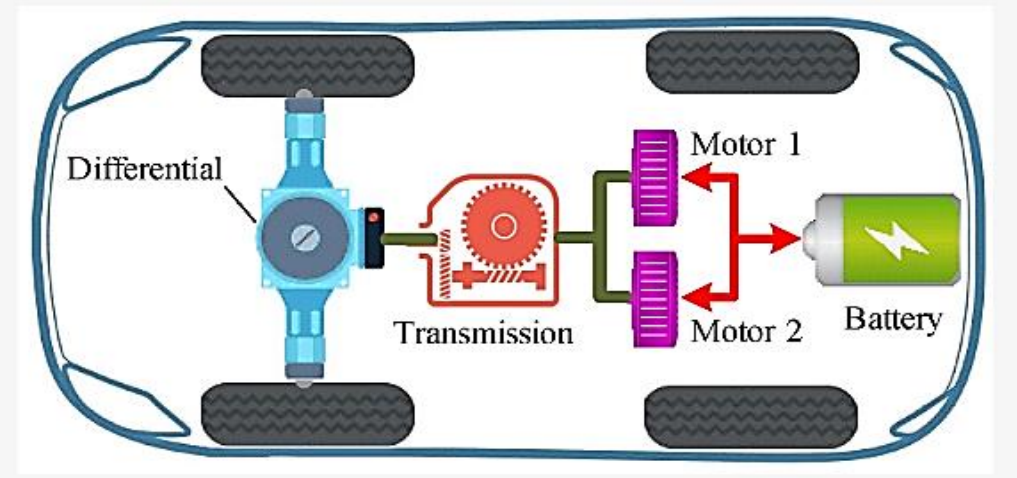


FIG I-13: Architecture of a Two Motor Electric Vehicle.

A) The Synchronous Motors: There are various configurations of synchronous motors, with the Permanent Magnet Synchronous Motor (PMSM) being the most widely discussed in academic literature. This type of motor is particularly valued for its technical characteristics, notably its high efficiency. In PMSMs, excitation is supplied by permanent magnets. Key advantages of this motor include superior torque-to-weight and power-to-weight ratios, as well as exceptional efficiency. However, a significant challenge is the high cost of the magnets, which prevents the motor from meeting the target sales price limitation [22].

Advantages

- ✓ The rotor has exceptionally low inertia.
- ✓ The motor exhibits outstanding torque and power performance.

Disadvantages

- o The cost remains relatively high.
- o It is difficult to maintain the magnets at the required temperature.
- o The control electronics are relatively complex.
- o The magnets are brittle, and assembling the magnetized rotor poses challenges.

B) Asynchronous Motor: Numerous manufacturers view the asynchronous motor as a viable solution. Distinctions are made between motors with slip rings and squirrel-cage designs. The squirrel-cage asynchronous motor is known for its durability and high power-to-weight ratio, contributing to good efficiency in the drive system. The asynchronous motor (ASM) is particularly suited for powering electric vehicles (EVs), leveraging advanced control methods. Currently, the most suitable control technique is field-oriented vector control, which enables the motor to operate at variable speeds with significant flexibility. Therefore, each propulsion application requires a specific type of motor. Similar to batteries, motors are not universal. Each motor offers distinct advantages and limitations, with cost and control complexity being the primary challenges [23].

Advantages

- Simple and robust construction: Asynchronous motors lack brushes and commutators, making them simpler and more durable compared to DC motors.
- Low cost: The straightforward design of asynchronous motors results in reduced manufacturing and maintenance costs.
- High energy efficiency: Asynchronous motors are highly efficient, which leads to lower energy consumption and cost savings during operation.
- Low maintenance: Asynchronous motors require minimal upkeep, reducing operational costs and downtime.
- Wide speed range: These motors can function over a broad range of speeds, making them versatile for various applications.
- High starting torque: Asynchronous motors can deliver high starting torque, which is crucial for applications that require rapid acceleration.

Disadvantages

- The maximum torque is relatively low.
- The cost is relatively high, primarily due to the power electronics and control systems required.

I.9 Battery Systems

Batteries can be classified into two categories: primary (non-rechargeable) and secondary (rechargeable) types. Primary batteries are designed for a single use and cannot be recharged, while secondary batteries are capable of being recharged after discharge. In Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs), secondary batteries are utilized to meet essential performance criteria, including high energy density, power density, long cycle life, and cost-effectiveness. Among the secondary batteries commonly used in EVs are lead-acid, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and lithium-ion (Li-ion) batteries. These batteries play a crucial role as energy storage systems in EVs, contributing to the vehicle's driving range and acceleration performance [24].

Introduction to Electrochemistry of Battery Cells

Battery cells function by converting chemical energy into electrical energy through electrochemical reactions. The basic structure of a battery cell includes a positive electrode, negative electrode, electrolyte, separator, and current collectors. During discharge, the anode undergoes oxidation, releasing electrons, while the cathode undergoes reduction by accepting electrons. The charging process reverses these reactions, restoring the electrodes to their original states. Ions in the electrolyte migrate due to concentration gradients and electric fields, while electron flow through the external circuit supplies power. Polarization within the battery results in a deviation from the equilibrium voltage, which is influenced by factors suchas the internal resistance of the cell components [25].

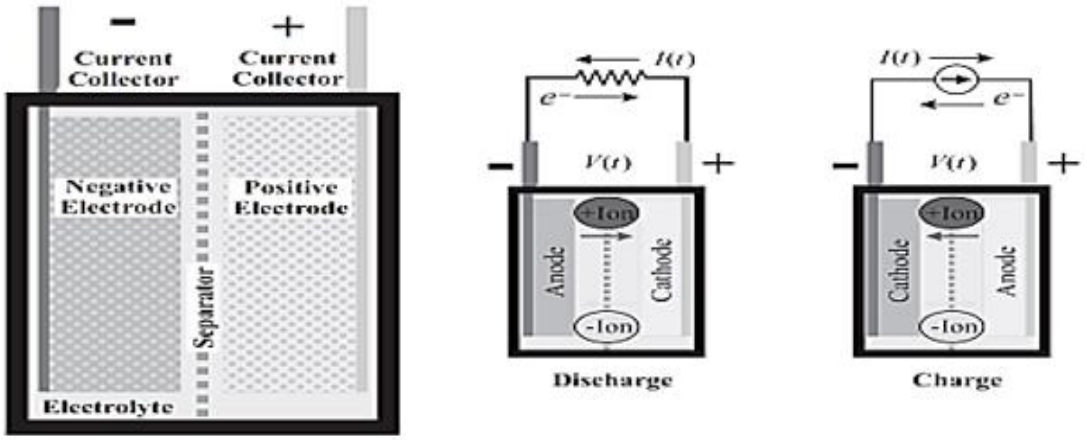


FIG I-14: Schematic diagram of an electrochemical cell

I.9.1 Lead-Acid Batteries

Lead-acid batteries, frequently used in EVs, undergo specific chemical transformations during their discharge and charge cycles. In the discharge process, the electrodes are converted into lead sulfate and water. During charging, lead sulfate is reversed back into lead dioxide at the positive electrode and sponge lead at the negative electrode. Valve-regulated lead-acid (VRLA) batteries are a refined version of lead-acid batteries, designed to recombine oxygen, thus minimizing water loss and enhancing operational performance, particularly under challenging conditions. VRLA batteries offer higher charging rates and do not require regular electrolyte level checks [26].

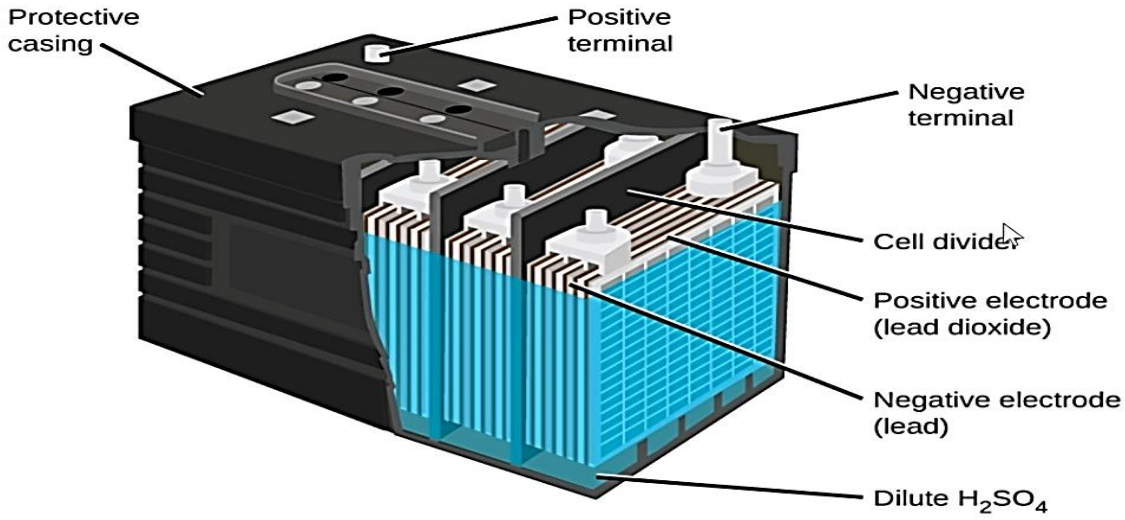


FIG I-15: Lead-Acid Batteries

I.9.2 NiCd and NiMH Batteries

Nickel-based rechargeable batteries, including NiCd and NiMH types, were developed over a century ago and offer superior performance compared to lead-acid batteries. These batteries provide longer cycle life, higher capacity, and faster charging rates. However, they are characterized by relatively high self-discharge rates. NiCd batteries use nickel hydroxide as the positive electrode and cadmium as the negative electrode, while NiMH batteries replace cadmium with hydrogen-absorbing alloys, offering environmental advantages. NiMH batteries generally deliver higher energy density and longer cycle life than NiCd batteries, making them more environmentally friendly and increasingly popular for use in EVs [26].

NiCd Batteries

NiCd batteries are available in various configurations, including pocket-plate, sintered-plate, and fiber-plate types, each offering distinct performance characteristics. The chemical

reaction in NiCd batteries involves the oxidation of cadmium and the reduction of nickel oxyhydroxide. These batteries utilize potassium hydroxide as the electrolyte, which remains relatively stable during charging and discharging, making it unsuitable for determining the state of charge (SOC). One significant drawback of NiCd batteries is the environmental impact of cadmium [26].

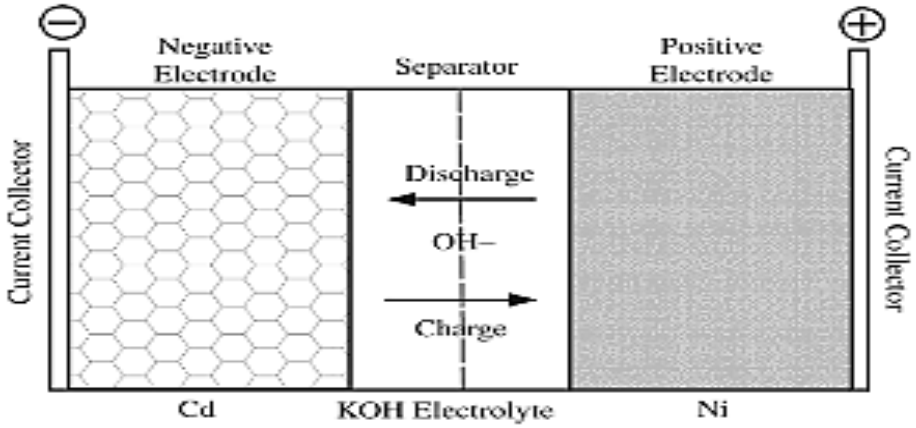


FIG I-16: schematic diagram of a NiCD battery

NiMH Batteries

NiMH batteries operate on similar principles as NiCd batteries but use hydrogen-absorbing alloys instead of cadmium. This substitution makes NiMH batteries more environmentally friendly. NiMH batteries offer higher energy density and longer cycle life compared to NiCd batteries. They use nickel hydroxide as the positive electrode and metal alloys for the negative electrode. The electrolyte, typically potassium hydroxide, remains stable, promoting longevity and superior performance. Additionally, the recombination of oxygen at the negative electrode helps minimize internal pressure, improving battery stability during cycling [26].

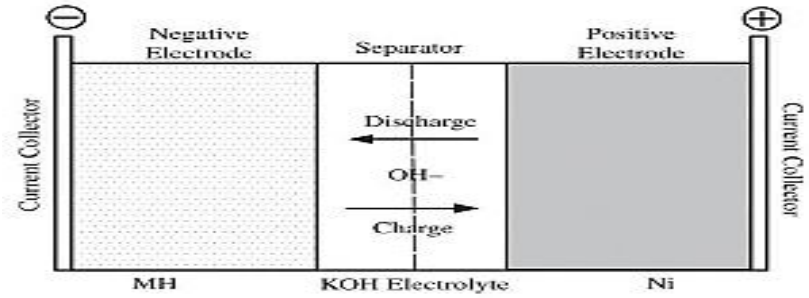


FIG I-17: schematic diagram of a NiMH battery

I.9.3 Lithium-Ion Batteries

Li-ion batteries have been developed to offer significantly higher energy density and power density than lead-acid and nickel-based batteries. They are widely utilized in portable electronics and EVs due to their superior charging and discharging capabilities, longer cycle life, and absence of the memory effect. Li-ion batteries rely on lithium intercalation compounds as the positive and negative electrodes, with lithium ions moving between the two electrodes during charge and discharge. Although Li-ion batteries are more expensive than lead-acid and nickel-based batteries, their cost is expected to decrease as production scales up. The chemical reaction within Li-ion batteries involves the intercalation of lithium ions between the anode and cathode, with the selection of electrode materials influencing performance. Safety concerns, such as thermal runaway and pressure build-up, are addressed by incorporating various safety mechanisms, including temperature shutdown, pressure relief vents, and over current protection [11].

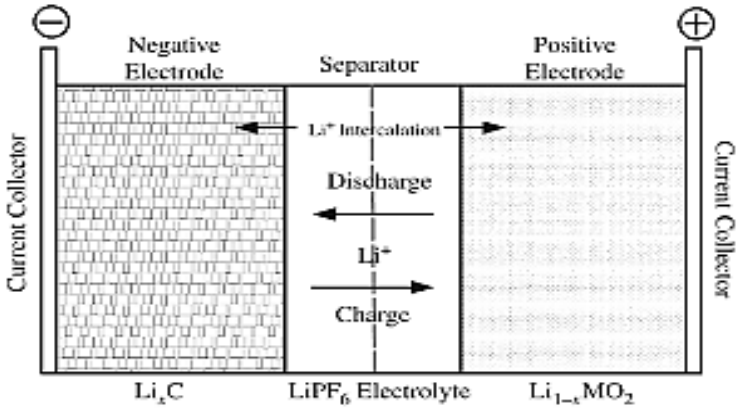


FIG I-18: schematic diagram of a Li-ion battery

I.10 Battery Life of an Electric Vehicle

Over time and with repeated charge/discharge cycles, the battery of an electric vehicle gradually wears out and loses some of its energy capacity. However, this degradation is slow, and it is estimated that an electric vehicle battery retains about 75% of its capacity after 10 years. As a result, the battery of an electric vehicle is designed to last as long as the vehicle itself.

The slow degradation of electric vehicle batteries is largely due to advancements in battery technology, particularly with the use of lithium-ion batteries. These batteries are designed to withstand thousands of charge cycles before their capacity significantly drops. Furthermore, electric vehicle manufacturers often offer warranties that cover the battery for 8-10 years or a

certain mileage (e.g., 100,000 to 150,000 miles), which gives consumers confidence in the longevity of their vehicles [7].

I.11 Battery Recycling

Electric vehicle batteries are made of valuable materials like lithium, cobalt, nickel, and aluminum, all of which can be recycled. However, recycling these batteries is a challenging and costly process that involves chemical processes. Instead of immediately recycling them, it is often better to repurpose the batteries for less demanding applications, extending their usefulness. This is one of the goals of **MOBILIZE**, which focuses on providing innovative energy storage solutions, among other initiatives [7].

I.12 Different charging modes for electric vehicles:

An EV charger is an electrical device that converts alternating current (AC) to regulated direct current (DC) for recharging a vehicle's battery and potentially powering other electrical systems within the vehicle. Charging an EV requires three essential functions: two electrical and one mechanical. The electrical functions include the rectification process (converting AC to DC) and the regulation of supply voltage to match the battery's charge acceptance characteristics. The mechanical function involves the user physically connecting the EV to the Electric Vehicle Supply Equipment (EVSE)**.**

The charging process involves a combination of methods for charging and termination. The charger’s core functions are:

1. **Charging** – transferring energy into the battery.
2. **Stabilizing** – optimizing the charging rate.
3. **Terminating** – knowing when to stop the charging process.

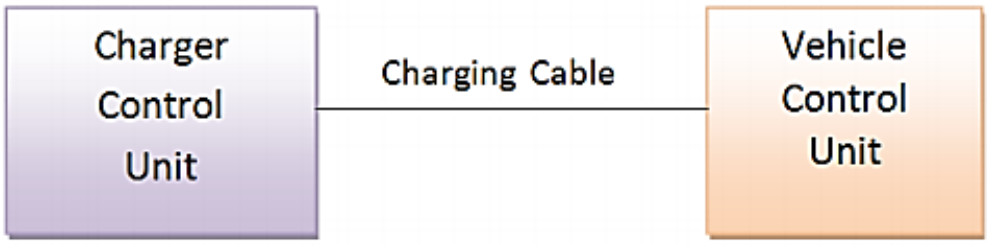


FIG I-19: Main parts of electric vehicle charger

The EV charging system consists of a charger control unit, charging cable, and vehicle control unit. Numerous studies in the literature focus on the different power electronics topologies of chargers and the technical aspects of charging technologies. This paper provides

a broad overview of charging technologies, aiming to offer a comprehensive understanding for EV manufacturers. Special attention is given to charging technologies for commercial vehicles, and all components of the EV charging system are discussed in detail [13].

I.13 The different EV charging methods

An EV charging systemis used to transfer energy from a constant voltage supply to a direct current, variable voltage EV battery, enabling the charging of the battery and/or operation of vehicle systems. There are three primary charging methods: conductive charging, inductive charging, and battery swapping.

In conductive charging, the battery is directly connected to the electricity provider via a cable. On the other hand, inductive charging operates through electromagnetic fields, transferring energy without physical contact between the EV and the charging infrastructure. While conductive charging is more efficient and cost-effective, ongoing R&D projects are focusing on inductive charging to improve user comfort and make it a potential feature for electric mobility.

The third method, battery swapping, involves exchanging discharged batteries with fully charged ones at a swapping station. However, for this method to work, batteries must be standardized in size, shape, and internal connections. This would limit OEM design flexibility and restrict battery placement options, leading many manufacturers to reconsider or reject this approach [13].

I.14 TheEV Charging Levels

The charging level describes the “power level” of a charging outlet. There are three levels in charging technology.

I.14.1 Level 1 Charging

Level 1 charging is a method that connects an electric vehicle (EV) to a standard grounded electrical receptacle (NEMA 5-15R), commonly known as “Home Charging.” The vehicle is equipped with an on-board charger capable of accepting energy from the existing alternating current (AC) supply. This method involves using a cord set to transfer AC power from the electric supply to the on-board charger. Level 1 charging complies with the National Electrical Code and is suitable for home use [13].

I.14.2 Level 2 Charging

Level 2 charging utilizes dedicated AC electric vehicle supply equipment (EVSE), found in both private and public locations. This method provides energy through an on-board charger that accepts power from AC supply, typically at power levels of 7 kW (32A single-phase) or 21 kW (three-phase). Level 2 is considered "Fast AC charging" and is widely used in homes, workplaces, and public charging stations. It requires dedicated EVSE and offers faster charging compared to Level 1 [13].

I.14.3 Level 3 Charging

Level 3 charging, also known as "Fast DC charging," uses dedicated direct current (DC) electric vehicle supply equipment to deliver energy from an off-board charger to the EV. This method enables high-power charging, with power levels that can recharge an EV's battery to over 80% in as little as 20 minutes. The charging process is typically faster than both Level 1 and Level 2, and the last 20% of charging time is slower. Level 3 charging is utilized in private and public locations and can significantly reduce charging time for EVs [13].

I.14.4 The EV Charging Modes

The charging mode defines the safety communication protocol between the EV and the charging station, with these standards being the same globally. One approach to EV charging is connecting the AC supply network (mains) to an on-board charger, while another method involves using an off-board charger to deliver direct current. High-power charging facilities can be used for fast charging in a short amount of time [13].

I.14.5 Mode 1 Charging (Household Socket and Extension Cord)

Mode 1 charging involves home charging using a standard power outlet and an extension cord, without additional safety features. This method, while common for private EV conversions, has been prohibited in several countries. It connects the electric vehicle (EV) to the AC supply network through standardized socket outlets, with a maximum of 16A and 250V AC single-phase or 480V AC three-phase at the supply side. The electrical installation must comply with safety regulations, including an earthing system, overload protection via a circuit breaker, and earth leakage protection. The sockets are designed with shutters to prevent accidental contact [13].



FIG I-20: Mode 1 type connection

I.14.6 Mode 2 Charging (Domestic Socket and Cable with a Protection Device)

Mode 2 charging connects the EV to the main power grid through a household socket outlet, using a special in-cable Electric Vehicle Supply Equipment (EVSE) with built-in protection. The cable includes an RCD, over-current protection, over-temperature protection, and protective earth detection. Power flows to the vehicle only when the EVSE confirms valid protective earth, no errors, the vehicle is plugged in, and has requested power. Mode 2 charging offers moderate safety and is the minimum standard for home charging. It uses standardized socket outlets with a control pilot and personnel protection (RCD), with the control box placed near the plug or EVSE [13].



FIG I-21: Mode 2 type connection

I.14.7 Mode 3 Charging (Specific Socket on a Dedicated Circuit)

Mode 3 charging connects the EV directly to the electrical network via a specific socket, plug, and dedicated circuit, with permanent control and protection functions installed. It is the only mode that meets electrical installation standards and supports load-shedding, allowing simultaneous operation of household appliances during charging or optimizing EV charging time. Mode 3 provides higher power levels than Mode 2 and is used in wired-in AC charging stations, either in public or private locations. The safety protocol is identical to Mode 2,

utilizing dedicated EVSE with a control pilot function connected permanently to the AC supply network [13].



FIG I-22: Mode 3 type connection

I.14.8 Mode 4 Charging (Direct Current Connection for Fast Charging)

Mode 4 charging connects the EV to the main power grid through an external charger, with control, protection functions, and the vehicle charging cable permanently installed. This wired-in DC charging station, used in public or private locations, has the charger as part of the station, not the vehicle.



FIG I-23: Mode 4 type connection

This charging mode involves connecting the EV to the AC supply network through an off-board charger, with the control pilot function extending to equipment permanently connected to the AC supply [13].

I.15 The EV Charging Sockets (Types)

The type of charging station (or vehicle inlet) refers to the connector used, with several different world standards. The terms are as follows:

- **Socket:** On the charging station.
- **Plug:** On the cable towards the charging station.
- **Inlet:** On the EV.
- **Connector:** On the cable towards the EV.

I.15.1 Type 1 (Single Phase Vehicle Coupler)

Used in the U.S. and Japan, also known as "SAE1772," Type 1 connectors support single-phase AC charging, with a fixed charging cable. The SAE J1772-2009 connector, often referred to as the Yazaki connector, is common in North America and is part of the IEC 62196-2 standard. It features five pins for two AC wires, earth, and two signal pins for proximity detection and control [13].



FIG I-24: Type 1 charging cables

I.15.2 Type 2 (Single and Three Phase Vehicle Coupler)

Common in Europe, Type 2 connectors, also called "Mennekes," support both single-phase and three-phase AC charging at higher power levels than Type 1. The cable is detachable, allowing it to charge both Type 1 and Type 2 vehicles with the appropriate cable, while Type 1 stations are fixed and cannot charge Type 2 vehicles [13].



FIG I-25: Type 2 charging cables

I.15.3 Type 3 (Single and Three Phase Vehicle Coupler with Safety Shutters)

Used in France and Italy, Type 3 connectors include shuttered contacts to prevent accidental contact with live parts. These shutters are mandatory in the UK and are designed to enhance

safety, particularly in "Vehicle to Grid" scenarios. Type 3 offers additional protection compared to Type 1 and Type 2 connectors [13].

I.15.4 Type 4 (Fast Charge Coupler)

Known as CHAdeMO, Type 4 connectors are used in Japan and Europe for DC fast charging. CHAdeMO delivers high-voltage (up to 500 VDC) and high-current (125 A) DC power, allowing fast charging of EVs up to 62.5 kW. It uses the CAN bus protocol for signaling and is included in IEC 62196 as Type 4 [13].



FIG I-26 Type 4 charging cables

I.15.5 DC Charging

DC charging uses off-board chargers to deliver energy to the EV, enabling high-speed charging at varying power levels. DC chargers can rapidly replenish up to half the EV battery's capacity in as little as 10 minutes, offering much faster charging than AC levels 1 and 2[13].

I.15.6 Inductive Chargers

Inductive charging uses an electromagnetic field to transfer energy between two objects, typically a charging station and the EV. The system uses two coils, one in the charger and one in the device, to create an alternating electromagnetic field. Advances such as resonant inductive coupling allow for greater distances and improved efficiency [13].

Advantages of Inductive Charging

- ✓ Protected connections
- ✓ Low infection risk
- ✓ Durability
- ✓ Increased convenience and aesthetics
- ✓ No cables required

Disadvantages of Inductive Charging

- Slower charging speed
- Higher cost
- Inconvenience

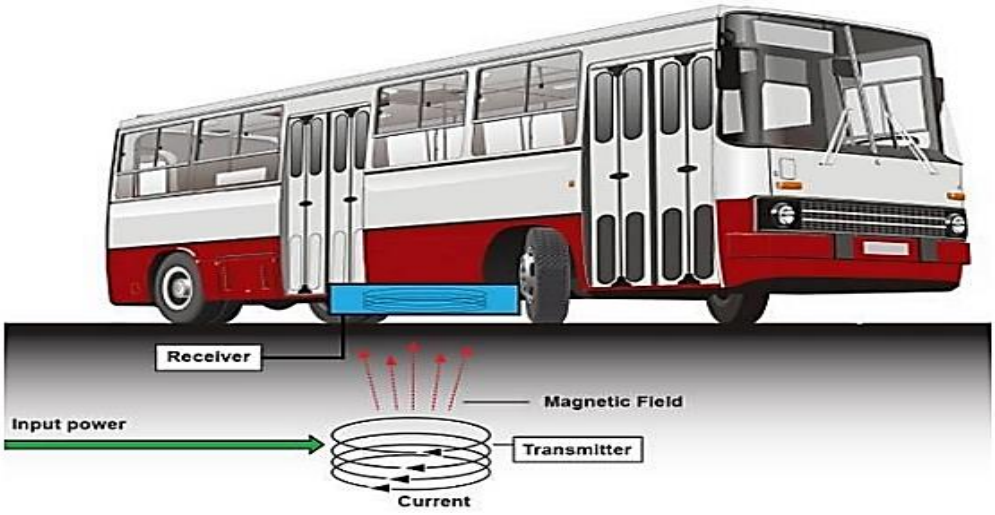


FIG I-27: An electric bus charging wirelessly at a static

I.16 Conclusion

This chapter has established Electric Vehicles (EVs) as a pivotal technology in this transition, examining their current state of the art, fundamental operation, and the critical factors influencing the choice of traction motor. Among the various motor technologies evaluated, Switched Reluctance Motors (SRMs) emerge as a highly compelling solution. Their inherent characteristics – including robust construction, high efficiency across a wide speed range, fault tolerance, cost-effectiveness, and suitability for high-torque applications – position SRMs as a particularly advantageous technology for meeting the demanding requirements of modern EV traction systems. This foundation underscores the significant potential of SRMs in accelerating EV adoption and achieving the overarching goal of reduced fossil fuel consumption.

Second Chapter

THE SWITCHED RELUCTANCE MOTOR

II.1 Introduction

The switched reluctance motor (SRM) represents an early approach to electromechanical energy conversion in rotating electrical machines, its conceptual origins tracing back to the nineteenth century. The fundamental principle behind its operation relies on the modulation of magnetic flux, oscillating between maximum and minimum values corresponding to the minimum and maximum reluctance, respectively. As illustrated in Figure II.1 (referencing the provided image showing Reluctance and Inductance curves relative to rotor position), this principle was initially harnessed either for generating high-frequency currents (approximately 10 kHz) during the nascent stages of radio technology or for the development of electromagnetic actuators or relays. In recent decades, SRMs have garnered significant attention and undergone substantial development, driven by their structural simplicity, considerable torque production capabilities, and advancements in the field of power electronics. While historically overshadowed by synchronous generators in large-scale power generation, induction motors in general-purpose applications, and direct current (DC) commutator machines, SRMs are now increasingly implemented in high-speed drives and industrial traction applications. This is attributable to their favorable torque characteristics, achieved with a current demand roughly 30% lower than that of comparable induction motors. Indeed, SRMs demonstrate enhanced performance relative to induction motors and offer straightforward speed regulation.

These motors are characterized by a simple and robust construction, cost-effectiveness, and dependable operation across a broad spectrum of speeds and power ratings. Currently, SRMs are finding increased application in diverse sectors such as domestic appliances, automotive and railway propulsion systems, and embedded systems, among others. This chapter will focus on presenting the SRM in detail. The subsequent sections of this study are devoted to the modelling and underlying concepts of SRMs, including a discussion of their operational principles, classifications, power supply configurations, and control methodologies.

II.2 Switched Reluctance Motor

A Switched Reluctance Motor operates through a reluctance torque. Unlike traditional DC motors with brushes, power can be transmitted to the windings inside the stator instead of the rotor. For optimal operation, it uses a switching inverter. The control characteristics of this motor are similar to those of DC motors with electronic commutation. These motors are applicable when sizing and power to weight ratio are critical.

This motor simplifies its mechanical design to limit current flow to a rotating part; however, it complicates the design because a certain type of switching system must be used to transmit power to the different windings. This mechanical design can also be used for a generator. The load can be switched to the coils in sequence to coordinate the current flow through rotation. Thus, these generators can also operate at high speeds compared to conventional motor types because the rotor is made of a single piece of magnetisable material, such as a split cylinder [27].

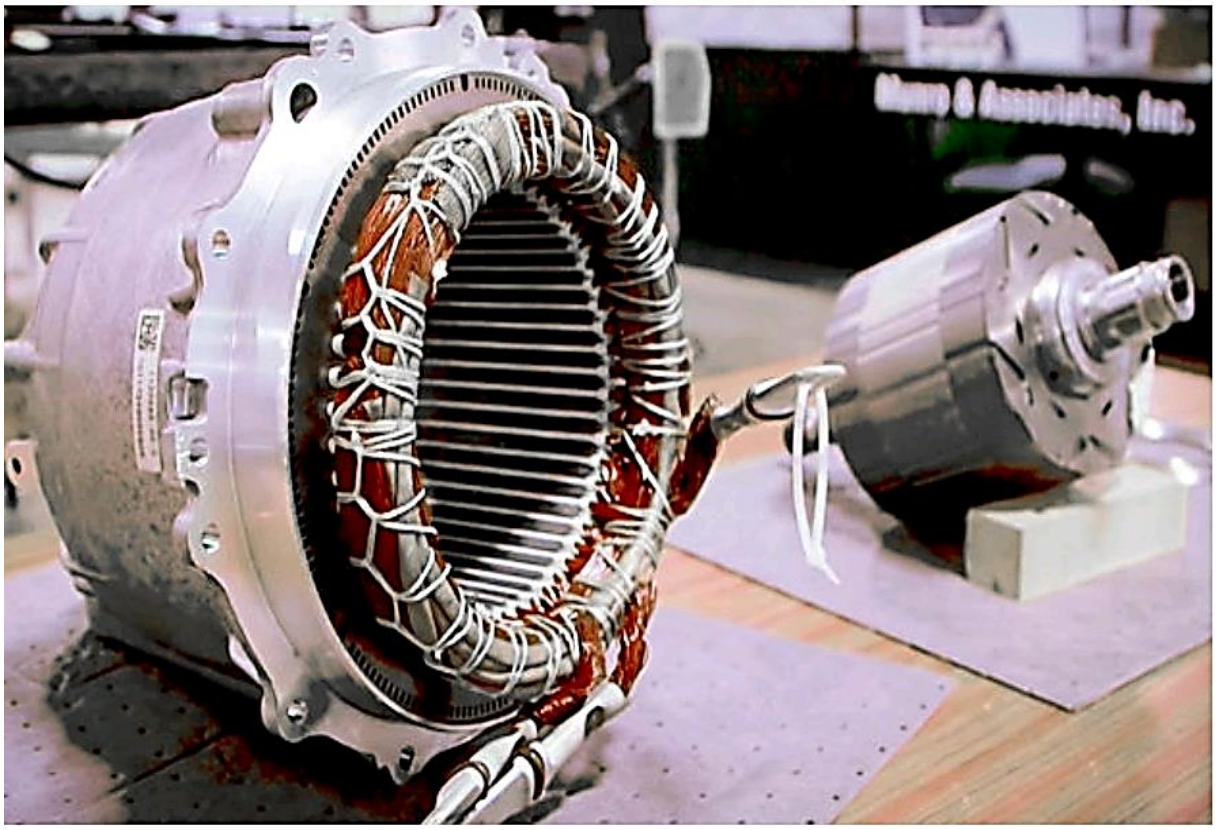


FIG 0-1: Switched Reluctance Motor

The reluctance of a magnetic circuit is a quantity that characterizes a volume element traversed by a magnetic flux. It is a function of the geometric dimensions of the element and the magnetic permeability of the material. The reluctance of a region of space traversed by a magnetic field is expressed by the following Relationship:

$$\mathbf{R} = \int \mathbf{dl}/\boldsymbol{\mu}\mathbf{s}$$

II.3 Classification of SRMs

In electrical engineering, it has been agreed to classify electrical machines according to the type of electrical energy (direct or alternating). However, this does not prevent some classifications from considering geometry, the type of movement (linear, rotary, or combined), etc. In conducting our bibliographic research, we found that SRMs do not conform to an

obvious classification. Indeed, for the same geometry, they can operate with direct current, such as the pure double-salient SRM, or with alternating current, such as the synchronous SRM, Vernier, hybrid, etc. Some authors have attempted to find its place in the "family tree" of electrical machines. Without a collector, the SRM is placed on the side of alternating current machines, as shown in the figure [28].

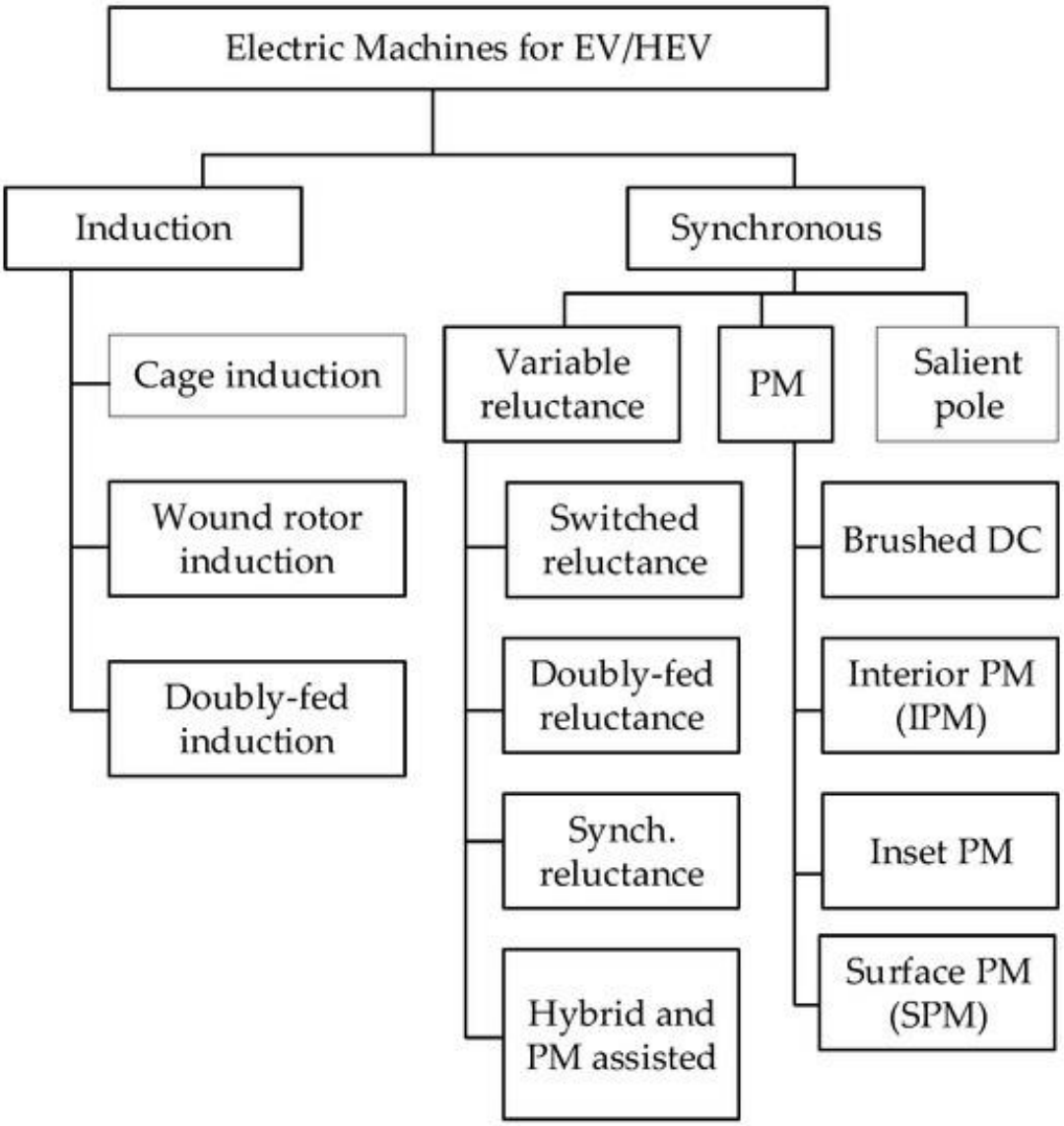


FIG 0-2 Electric Machines for EV/HEV

II.4 Constitution

Among the various existing SRM structures, we have chosen to use a double-salient Switched Reluctance Motor of the "6/4" type. The figure shows the structure of this machine.

This motor features a toothed structure where the pitch is not the same at the stator and rotor:

- **The Rotor:** It is not magnetized. The rotor is made of a stack of identical ferromagnetic sheets cut out. This stack is solidly attached to the transmission shaft. It contains neither electrical conductors nor magnets, which gives it great robustness and extreme simplicity.
- **The Stator:** It is also made of stacked ferromagnetic sheets. Two diametrically opposed poles receive two windings connected in series, forming a phase. This machine can have two, three, four (or even more) phases. In our project, we have chosen three phases. The stator has 6 teeth, while the rotor has only 4: these machines are often classified according to the number of stator and rotor teeth, so this is a "6/4" machine [29][30].

Then:

- Stator Pitch:

$$\alpha s = \frac{360°}{6} = 60°$$

- Rotor Pitch:

$$\alpha r = \frac{360°}{4} = 90°$$

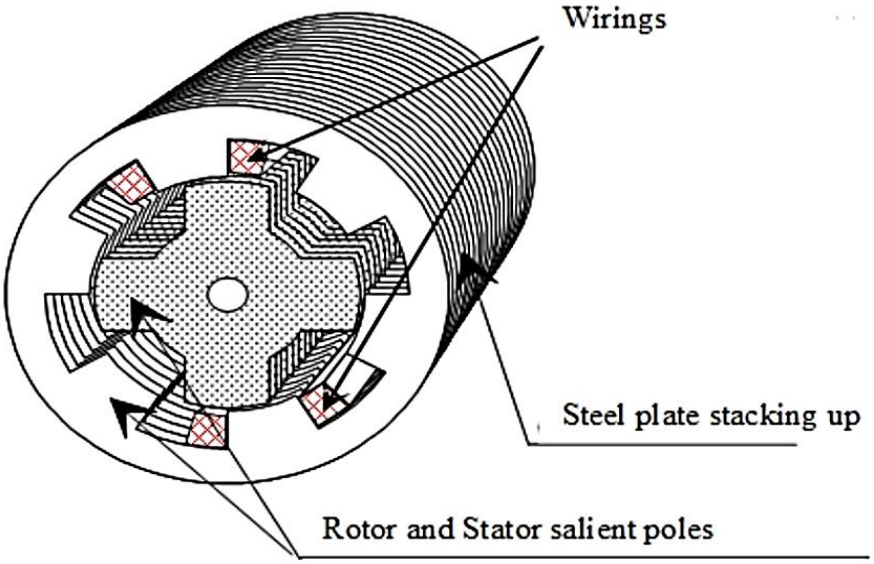


FIG 0-3: Electromagnetic structure of the 6/4 Switched Reluctance Motor (SRM) [17].

II.5 Basic Structure of an SRM

The operating principle of a Switched Reluctance Motor can be explained using a simple single-phase elementary structure, as shown in the figure below:

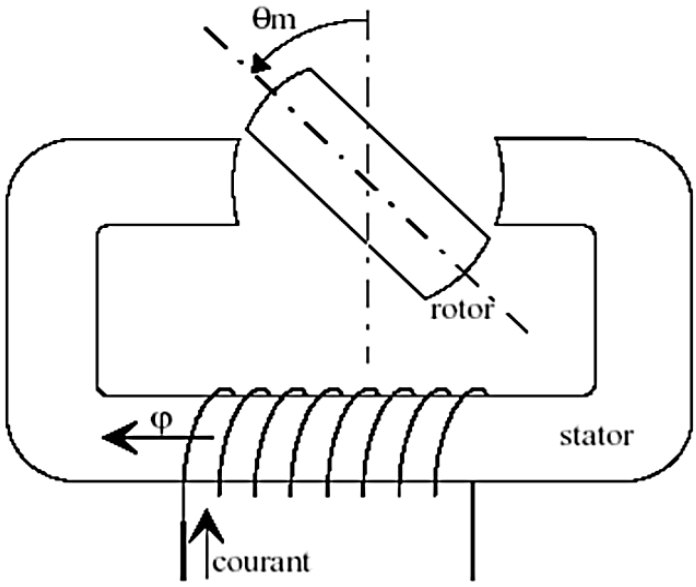


FIG 0-4: Elementary structure of a Switched Reluctance Motor [17].

The movement of the machine results from the rotor's tendency to align itself with the magnetic axis of the stator phase. This structure presents two significant rotor positions:

- An opposition position, where the magnetic circuit exhibits maximum reluctance or minimum inductance, as shown in figure (2-5).

- A conjunction position, where the reluctance is at its minimum and the inductance is at its maximum, as illustrated in figure (2-5) [17].

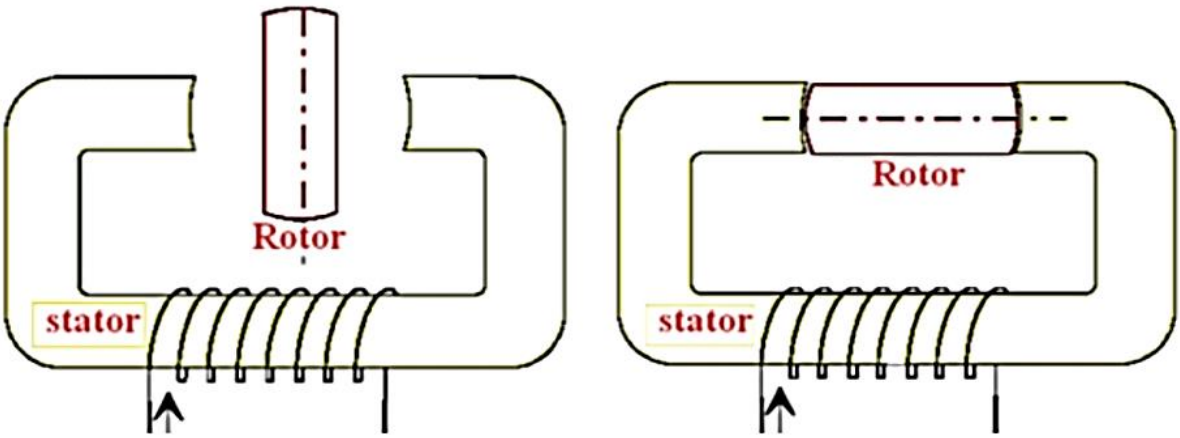


FIG 0-5: The opposition position and the conjunction position of the rotor relative to the two extreme reluctances [17].

Starting from the opposition position, for the ferromagnetic rotor piece to begin rotating, it follows the principle that a circuit left to itself in a magnetic field moves under the effect of Laplace forces until the flux passing through it is maximal.

The fixed electromagnet is energized up to the conjunction position $\theta m = \frac{\pi}{2}$, following the rule of maximum flux or minimum reluctance, and so on…

Given that the expression for the electromagnetic torque is:

$$\mathbf{Cem} = \frac{\mathbf{1}}{\mathbf{2}} \mathbf{I}^{\mathbf{2}} \frac{\boldsymbol{\delta \mathbf{L}}}{\boldsymbol{\delta \theta}}$$

Supplying the machine with a constant voltage during the phase when inductance is increasing or decreasing (as shown in the figure) enables the desired mode of operation [29].

Motor **(Cem> 0)** during the increasing phase of inductance $\frac{\boldsymbol{\delta \mathbf{L}(\theta)}}{\boldsymbol{\delta \theta}} > \mathbf{0}$.Generator **(Cem<0)** during the decreasing phase inductance $\frac{\boldsymbol{\delta \mathbf{L}(\theta)}}{\boldsymbol{\delta \theta}} < \mathbf{0}$.

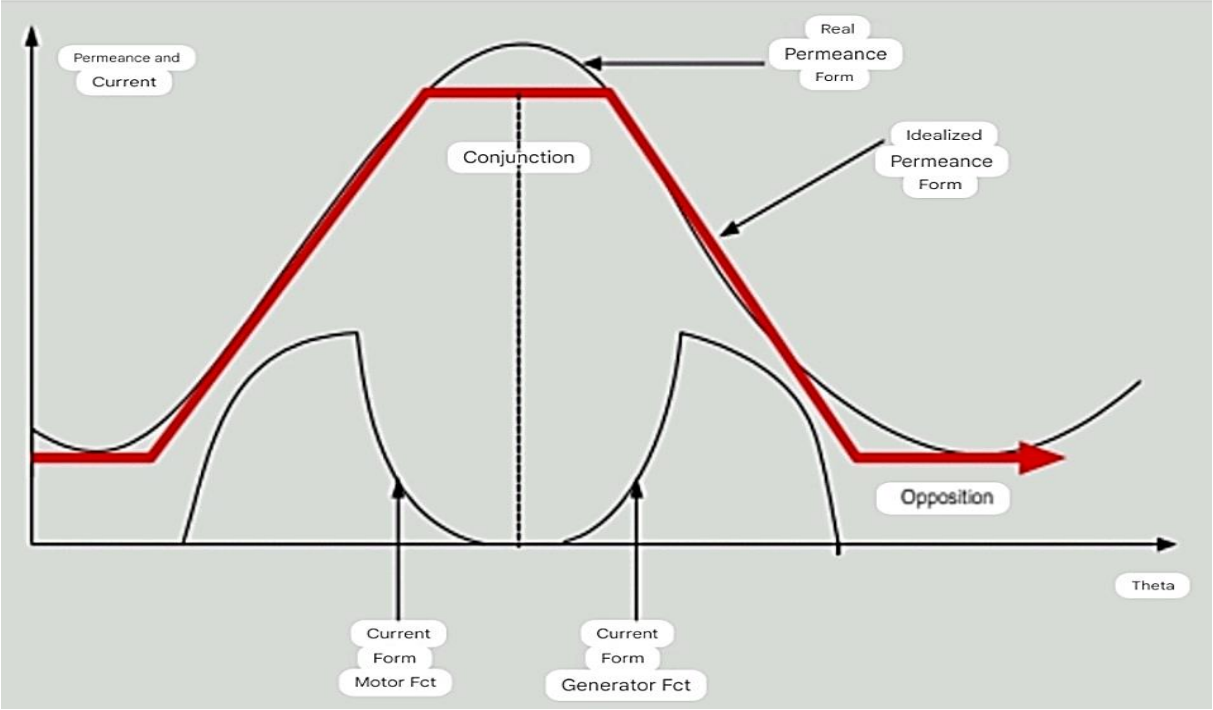


FIG 0-6: Characteristics of the SRM as a function of position [18].

II.6 Operating Mode of a Switched Reluctance Motor

The operating principle of a Switched Reluctance Motor is straightforward. Consider a piece of iron: if it is held in a magnetic field, the iron piece will align itself with the position of minimum reluctance and magnetically lock in place. The same principle applies to the Switched Reluctance Motor. As its name suggests, a switching inverter is necessary for the operation of a Switched Reluctance Motor. It operates on the principle of variable reluctance, meaning the rotor always tries to align itself along the path of lowest reluctance. The part of the rotor with minimum reluctance attempts to align with the stator's magnetic field. Consequently, a reluctance torque is developed in the rotor. This motor exploits the fact that the forces of a magnetic field on iron in the rotor can be up to ten times greater than the magnetic forces on current-carrying conductors.

In our motor, let's consider the following notation for better Understanding:

Stator Poles:

- Axis of poles AA' for phase A.
- Axis of poles BB' for phase B.
- Axis of poles CC' for phase C.

Rotor Poles:

- Axis of poles aa' for the rotor at Position 1.

- Axis of poles bb' for the rotor at Position 2.

Now, input is given to phase A, while phases B and C are neither maximal nor minimal. Then, the axis of stator poles AA' and the axis of rotor poles aa' are aligned. Figure 2-7 indicates that phase A has reached the position of minimum reluctance. This is because the air gap between the stator and rotor is very small, and they have a position of minimum reluctance relative to the other poles,then:

$$\mathbf{T = \frac{dLa}{d\theta} = 0}$$

Now, phase A will be deactivated and phase B will be energized. Then, the axis of the rotor bb' becomes the axis of the stator BB'. Move in a clockwise direction according to our diagram. By changing the polarity of the motor, it can easily be reversed. The torque evolves as the reluctance changes from maximum to minimum. The developed torque is equal to:

$$\mathbf{T = \frac{1}{2} i^2 \frac{dLb}{d\theta}}$$

The movement of the rotor depends on the number of poles, and in our case, we obtain a rotation of 30 degrees by energizing one phase at a time. Here, the torque is nothing but the movement of the rotor itself. When the shaft reaches the BB' position, there is no torque.

$$\mathbf{T = \frac{dLb}{d\theta} = 0}$$

Now, phase B will be deactivated and phase C will be activated. Then, torque is developed because the axis of the rotor aa' is aligned with the axis of the stator CC'. The rotor continues to rotate for an additional 30 degrees.

Again, C will be turned off and A will be activated. The operation of the motor continues until the input power is supplied. Here, you can observe that the motor rotates on its own. Thus, Switched Reluctance Motors (SRMs) are self-starting motors.



FIG 0-7: Structures of SRMs for different combinations of teeth and phases[19].

According to the rule of maximum flux corresponding to minimum reluctance, and the cycle repeats periodically.

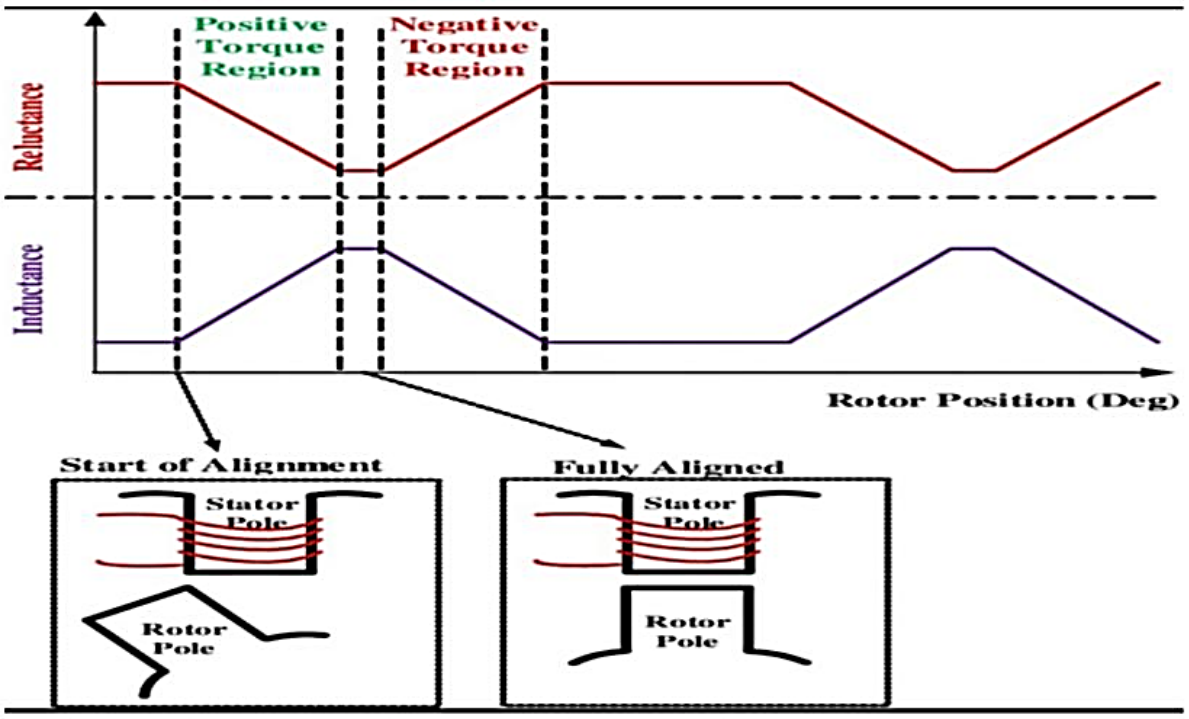


FIG 0-8: Elementary structure of the Switched Reluctance Motor (SRM) and extreme positions of the rotor tooth[19].

II.7 Types of Switched Reluctance Motors

The categorization of Switched Reluctance Motors (SRMs) can be done based on their construction as linear SRMs and rotary SRMs.

- **Linear SRM :** Linear SRMs, also known as linear switched reluctance motors, are referred to as servomotors in the market. They consist of a single-stage stator and rotor.
- **Rotary SRM:** Rotary SRMs, or rotary switched reluctance motors, are available in two types: radial field and axial field. Axial field SRMs are further classified into two types: single-stack and multi-stack. This rotary SRM includes more than one rotor and stator [31].

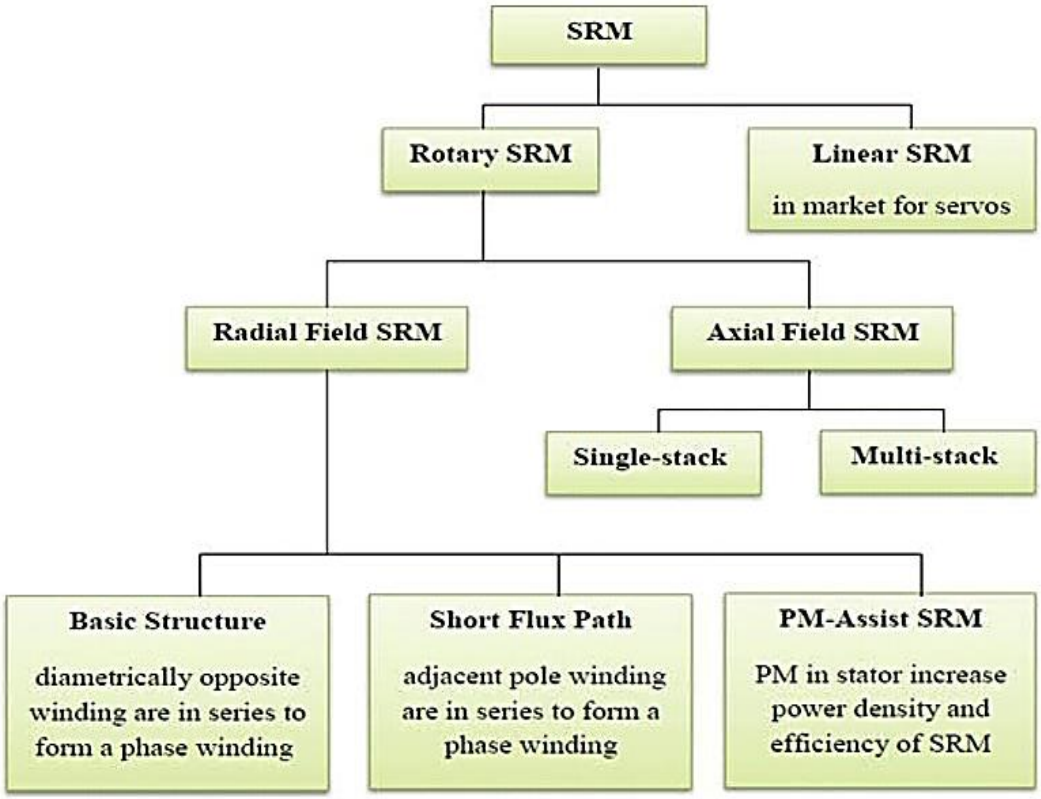


FIG 0-9: Classification of SRMs according to the type of movement, flux, and excitation mode.

II.8 Topologies of Rotary SRMs

SRMs can be rotary or linear in motion, but in our case, we will focus on rotary machines. There are several geometric configurations for rotary SRMs; the most common are those that consider the number of stator poles to be higher than the number of rotor poles (although in some cases, the rotor may contain more teeth than the stator). The choice of the number of teeth

and phases should be made in relation to the intended application and the desired performance. The criteria that can influence the choice for a particular topology include, among others:

- The value of the torque and its shape during starting, braking, and steady state.
- The type of power supply (three-phase, single-phase, etc.) and the control circuit used.
- The magnetic flux paths and iron losses produced.

II.8.1 Pure SRMs

SRMs known as "pure" have a salient structure on the rotor and stator, with an "active" stator where the windings are located and a "passive" rotor (without windings or magnets). Powered with a rectangular voltage or current waveform (square wave supply), they induce torques with a pulsed character, which is considered a disadvantage. Various types of pure SRM structures can be cited:

- Double-toothed structures with large teeth, with 2 teeth per phase (figure below).
- Double-toothed structures with large teeth, with more than 2 teeth per phase.
- Stator-poled structures with toothed ("small teeth") where one winding excites several teeth at once: this is referred to as "global winding."



FIG 0-10: Pure SRM with large teeth [17].

II.8.2 Vernier Effect SRMs

Vernier Effect SRMs have identical structures to pure SRMs, except that they have distributed windings and are powered by sinusoidal alternating current rather than square waves. There are machines called “Vernier with a large number of teeth,” which have two salient armatures on each armature; the teeth are identical and equally spaced, but the numbers of stator and rotor teeth are slightly different (similar to that of a smooth rotor synchronous machine), which makes it possible to obtain a sinusoidal permeance. There are also machines called “Vernier with large teeth,” in which each stator pole itself constitutes the tooth. The number of poles is then relatively low, and the torque-speed performance is comparable to that of asynchronous and synchronous machines with magnets and with similar supply frequencies [32].



FIG 0-11: Vernier Effect SRM [17].

II.8.3 Hybrid SRMs

Hybrid SRMs sometimes have the same structure as the two previous types, but they are also equipped with permanent magnets in order to improve their performance. The addition of magnets in double-salient structures makes it possible to compensate for an excessively high air gap. Two double-salient magnet machines derived from SRMs: one implements magnets placed on the rotor (figure II.4), with the machine resembling interior permanent magnet synchronous machines; the second retains the passive rotor of the pure SRM and uses magnets placed on the stator: we then obtain a double-salient machine with stator permanent magnets (DSPMM) called a “polarized SRM.”[33].

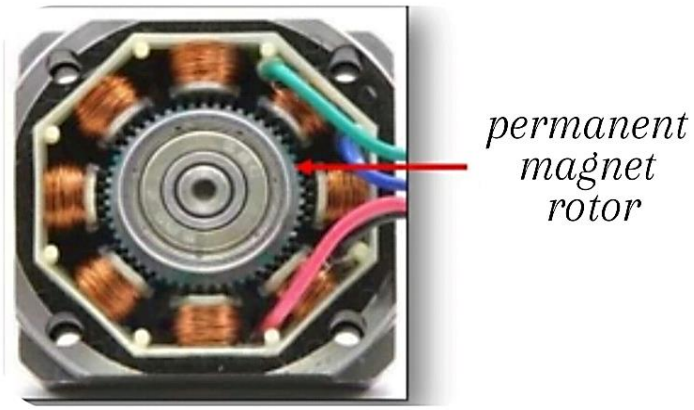


FIG 0-12: Hybrid SRM[17].

II.9 Applications of SRMs

In Switched Reluctance Motor (SRM) applications, both energy and economics play a crucial role. The Switched Reluctance Motor is considered, nowadays, for applications ranging from low-power servomotors to high-power traction drives. Motors with power ranging from 4 to 22 kW are currently commercially available for numerous applications. Typical applications include [34]:

- Household appliances such as washing machines, vacuum cleaners, fans.
- Machine tools: Planers, vertical lathes, drills.
- General machinery: Fans, pumps, compressors.
- Food mixing machines.
- Lifting equipment: Elevators, winches, conveyors.
- Power generation equipment: Load control of wind turbine rotor blades.
- Plastic manufacturing: Extrusion machines, injection molding machines.
- Stationery machines.
- Metal rolling mills.
- Coil winding and unwinding machines.
- Machines for oil fields, including vertical pumps, beam pumps, well testing machines.
- Mechanical presses such as screw presses.
- Mining machines, including shears, conveyors, winches, boring machines, ball mills, coal crushers.
- Electric vehicles.

II.10 Advantages of SRMs

- It does not require an external ventilation system. Airflow is maintained between the slots.
- The rotor has no windings, therefore, there is no need to maintain the brush-commutator assembly.
- Since there are no permanent magnets, such motors are available at a lower price.
- A simple three-phase or two-phase pulse generator is sufficient to drive the motor.
- The direction of the motor can be reversed by changing the phase sequence.
- Self-starting and does not require external arrangements.
- Starting torque can be very high without excessive inrush currents.
- High fault tolerance.
- Phase losses do not affect motor operation.
- High torque-to-inertia ratio.
- A high starting torque can be achieved.

II.11 Disadvantages of SRMs

- Creates torque ripple during high-speed operation.
- An external rotor position sensor is required.
- The noise level is high.
- At higher speeds, the motor generates harmonics; to reduce this, we need to install larger capacitors.
- Since there are no permanent magnets, the motor must be designed to withstand high input current. This increases the KVA requirement of the converter.

II.12 Torque-Speed Characteristics

The torque-speed operating point of a Switched Reluctance Motor (SRM) is essentially programmable and determined almost entirely by the control system. This is one of the characteristics that makes the SRM an attractive solution. The envelope of operating

possibilities is, of course, limited by physical constraints such as supply voltage and the permissible heating of the motor under increased load. Generally, this envelope is described by Figure 2-13.

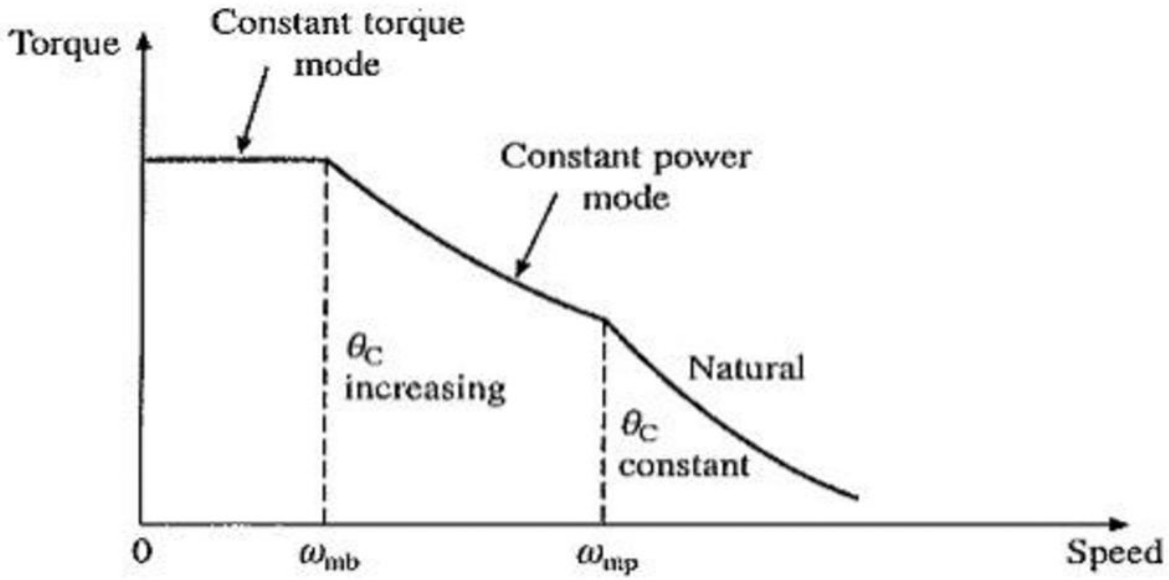


FIG 0-13: Torque-Speed Characteristics

Like other motors, the torque is limited by the maximum allowable current and the speed by the available bus voltage. As the shaft speed increases, a current limit region persists until the rotor reaches a speed where the motor's back-EMF is such that, given the DC bus voltage limitation, we can no longer get current into the winding, therefore no more torque from the motor. At this point, called the base speed, and beyond, the output power of the shaft remains constant, and at its maximum. At still higher speeds, the back-EMF increases, and the output power of the shaft begins to drop. This region is characterized by the product of torque by the square of the speed remaining constant[20].

II.13 Energy/Co-energy and Electromagnetic Torque

Electromagnetic torque is one of the main physical quantities characterizing an electric motor. To obtain the expression for the torque, several approaches exist: the method that uses magnetic energy and co-energy is among the most used.

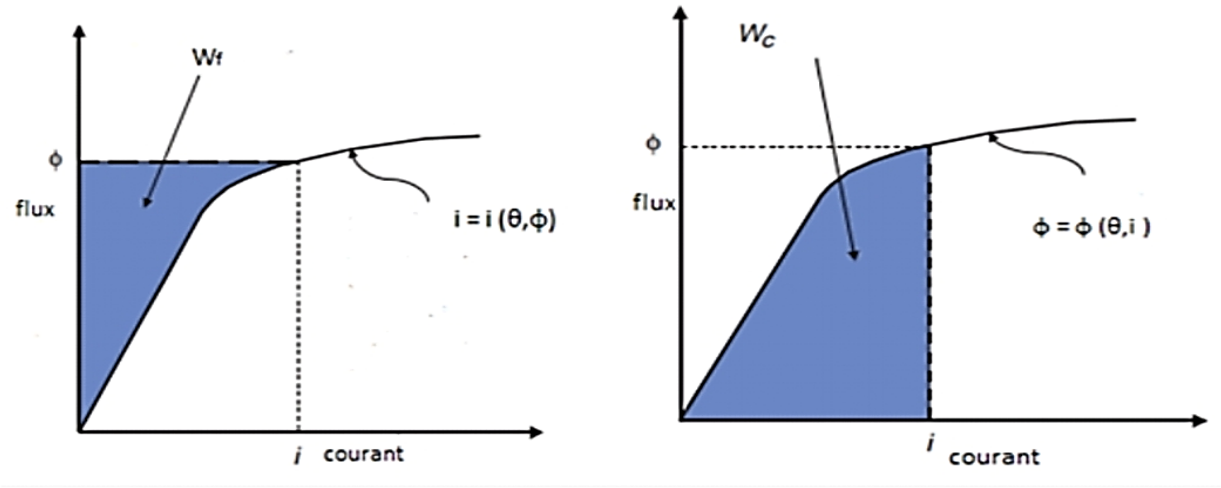


FIG 0-14: Electromagnetic Energy and Co-energy in a Magnetic Circuit[20].

II.14 The Electromagnetic Equation of an SRM

Although the operation of the SRM motor seems simple, a precise analysis of the motor's behavior requires a formal and relatively complex mathematical approach. The instantaneous voltage across a single phase of an SRM motor winding is related to the flux linkage in the winding according toFaraday's-law [20]:

$$\mathbf{v = i.Rm + \frac{d\Phi}{dt}} \qquad (\mathbf{2.1})$$

Due to the double-salient construction of the SRM motor (both the rotor and stator have salient poles) and because of the magnetic saturation effects, in general, the flux linkage in an SRM phase varies as a function of the rotor position, θ, and the motor current. Thus, equation (2.1) can be extended.

$$\mathbf{v = iRm + \frac{\delta\varphi}{\delta i}\frac{di}{dt} + \frac{\delta\varphi}{\delta\theta}\frac{d\theta}{dt}} \qquad (\mathbf{2.2})$$

II.14.1 General Torque Equation

Equation (2.2) governs the transfer of electrical energy to the magnetic field of the SRM. In this section, the equations that describe the conversion of energy from the field to mechanical energy are developed. Multiplying each side of equation (2.1) by the electric current, i, gives an expression for the instantaneous power in an SRM.

$$\mathbf{vi} = \mathbf{iRm} + \mathbf{i}\frac{\mathbf{d\theta}}{\mathbf{dt}} (\mathbf{2.3})$$

The sum of the mechanical output power of the SRM and any power stored in the magnetic Field[21].

$$\mathbf{i}\frac{\mathbf{d\theta}}{\mathbf{dt}} = \frac{\mathbf{dWm}}{\mathbf{dt}} + \frac{\mathbf{dWf}}{\mathbf{dt}} \qquad (\mathbf{2.4})$$

When:

- $\frac{\mathbf{dWm}}{\mathbf{dt}}$ is the instantaneous mechanical power
- $\frac{\mathbf{dWf}}{\mathbf{dt}}$ is the instantaneous power that is stored in the magnetic field.

Because power, by its own definition, is the rate of change of energy over time,

- Wm: is the mechanical energy
- Wf: is the energy of the magnetic field.

It is well known that mechanical power can be written as the product of torque and speed.

$$\frac{\mathbf{dWm}}{\mathbf{dt}} = \mathbf{t\omega} = \mathbf{t}\frac{\mathbf{d\theta}}{\mathbf{dt}} (\mathbf{2.5})$$

Substituting from equation (2.5) into equation (2.4) gives :

$$\mathbf{i}\frac{\mathbf{d\theta}}{\mathbf{dt}} = \mathbf{t}\frac{\mathbf{d\theta}}{\mathbf{dt}} + \frac{\mathbf{dWf}}{\mathbf{dt}} (\mathbf{2.6})$$

Solving equation (2.6) for torque yields the equation:

$$\mathbf{t}(\boldsymbol{\theta}, \boldsymbol{\varphi}) = \mathbf{i}(\boldsymbol{\theta}, \boldsymbol{\varphi})\frac{\mathbf{d\varphi}}{\mathbf{d\theta}} - \frac{\mathbf{dWf}(\boldsymbol{\theta}, \boldsymbol{\varphi})}{\mathbf{d\theta}} (\mathbf{2.7})$$

For constant flux, equation (2.7) simplifies to:

$$\mathbf{T} = -\frac{\boldsymbol{\delta}\mathbf{Wf}}{\boldsymbol{\delta\theta}} (\mathbf{2.8})$$

Since it is often desirable to express the torque in terms of current rather than flux, the torque can also be expressed in terms of co-energy, Wc instead of energy.

To introduce the concept of co-energy, let's first consider graphical interpretation of the field energy. For a constant shaft angle $\frac{d\theta}{dt} = 0$, integrating equation (6) shows that the magnetic field energy can be given by:

$$W_f = \int_0^{\varphi} i(\theta, \varphi) d\varphi \qquad (2.9)$$

For a fixed angle,let the magnetization curve define the flux as a function of current, rather than current as a function of flux. The shaded area under the curve,

$$W_c = \int_0^{i} \varphi(\theta, i) di \qquad (2.10)$$

Equation (2.10) is defined as the co-energy of the magnetic field. From the figures, we see that the area defining the field energy and co-energy can be described by the relationship :

$$Wc + Wf = i\varphi \qquad (2.11)$$

Differentiating both sides of equation (11) gives:

$$dWc + dWf = \varphi di + id\varphi \qquad (2.12)$$

Resolution of the differential field energy in equation (2.12) and substitution into equation (2.7):

$$T = \frac{i\varphi d - (\varphi di + id\varphi - dWc(\theta, i)}{d\theta} (2.13)$$

To simplify, the general equation of the torque, equation (2.13), is generally simplified for constant current values. The differential co-energy can be written in terms of its partial derivative as :

$$dWc(\theta,i) = \frac{\delta Wc}{\delta \theta} d\theta + \frac{\delta Wc}{\delta i} di \qquad (2.14)$$

From equation (2.13) and equation (2.14), we can show the following equation under constant current:

$$T = \frac{\delta Wc}{\delta \theta} \qquad (2.15)$$

When magnetic saturation is neglected, the relationship between flux and current is given by:

$$\varphi = L(\theta).i \qquad (2.16)$$

The motor inductance does not vary, we substitute equation 16 into equation (2.10):

$$\mathbf{Wc} = \frac{\mathbf{1}}{\mathbf{2}}\mathbf{i^2 L(\theta)} \quad \mathbf{(2.17)}$$

We substitute equation (2.17) into equation (2.15):

$$\mathbf{T} = \frac{\mathbf{1}}{\mathbf{2}}\mathbf{i^2}\frac{\mathbf{dL}}{\mathbf{d\theta}} \quad \mathbf{(2.18)}$$

We also have the electromagnetic power :

$$\mathbf{P\,em} = \mathbf{f.W} \qquad \mathbf{(2.19)}$$

With f being the electrical supply frequency, which can be written from the motor's rotational pulse.

$$\mathbf{f} = \mathbf{Nr.}\frac{\mathbf{\Omega}}{\mathbf{2\pi}} \quad \mathbf{(2.20)}$$

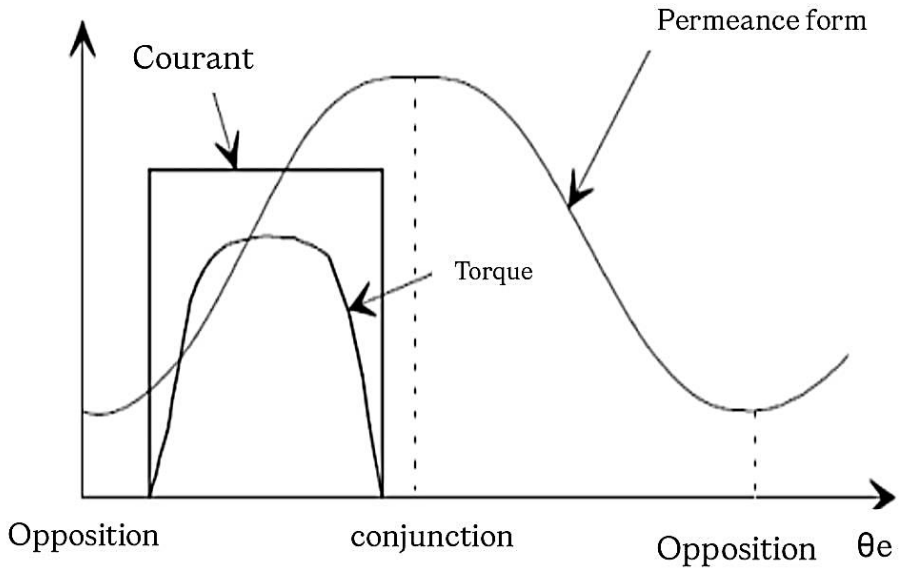


FIG 0-15: Torque variation as a function of rotor position [20].

II.15 Mechanical Equation

If we neglect dry friction and assume a linear load torque, we can define a linear mechanical model of the form

$$\mathbf{\Omega} = \frac{\mathbf{d\theta}}{\mathbf{dt}}$$

$$\mathbf{Te} = \mathbf{J}\frac{\mathbf{d\Omega}}{\mathbf{dt}} + \mathbf{fr\Omega} + \mathbf{TL} \qquad \mathbf{(2.21)}$$

II.16 Selection of a study structure

Our study focuses on switched reluctance motors (SRM) in generator operation with a 6/4 ratio. Studying this configuration amounts to analyzing the overall performance of switched reluctance motors with a larger number of poles having the same operating principles. It can be described from the study of an elementary single-phase structure or a 6/4 SRM. The converter-generator assembly is then analyzed for its control. The dimensions of the machine are those used by the works of who presents detailed parameters of the 6/4 SRM that we were inspired by.

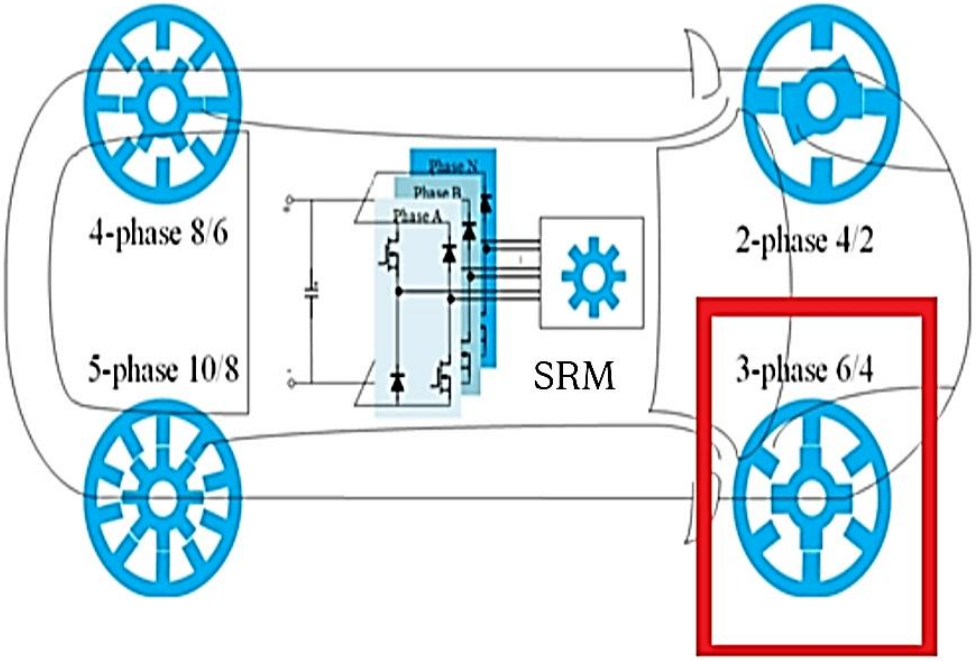


FIG 0-16: Structure of choice of SRM

II.17 Power supply of the SRM

The type of converter supplying the SRM depends on the motor geometry, the number of phases, and the application specifications. SRMs are also equipped with position sensors to detect the rotor position in order to synchronize the phase power sequences. The asymmetric bridge topology is the most popular and widely use[33].

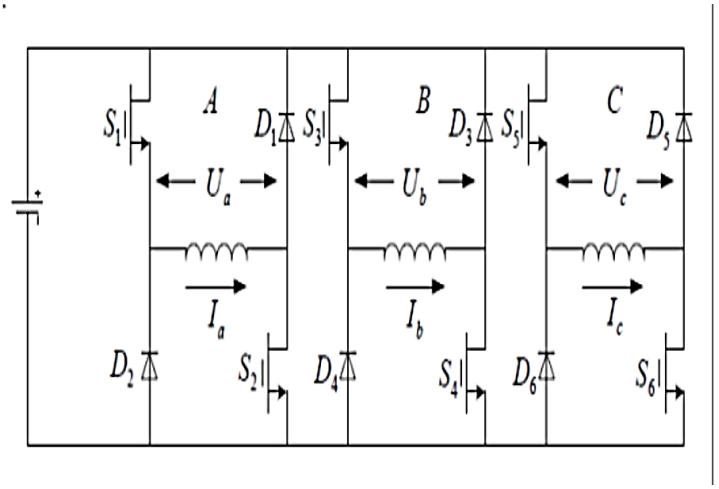


FIG 0-17: Asymmetric converter topology[26].

There are three operating modes of this converter topology, which are defined as : the magnetization mode, the freewheeling mode, and the demagnetization mode. As shown in Figure (2.17), the current direction of the three modes is indicated by the red arrow. By activating switches S1 and S2, phase A is excited by the voltage source and the phase current starts to increase. This process is called magnetization. By deactivating only S1 while maintaining S2, diode D2 is conducted, and the voltage supply is cut off. This process is called freewheeling, and the current will decrease slowly during this period. When both switches S1 and S2 are closed, diodes D1 and D2 are conducted, and negative voltage is applied to the phase winding. This process is called demagnetization. The phase current will drop significantly under the demagnetization voltage[34], and the current waveform is illustrated in Fig (2.18).

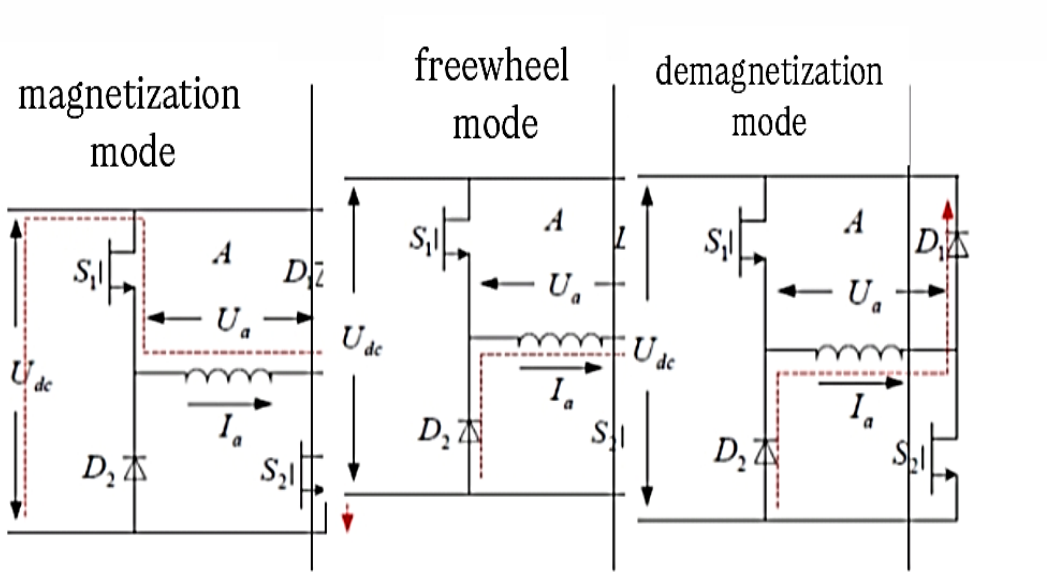


FIG 0-18: The operating modes of an asymmetric converter.

Table 0-1: Conduction sequences of the asymmetric half-bridge converter

	S1	S2	Phase voltage
1	Conductor	Conductor	+Vdc (magnetization mode)
2	Blocked	Conductor	0 (freewheel mode)
3	Blocked	Blocked	-Vdc (demagnetization mode)

Thanks to its ability to independently power the phases, this type of converter makes the machine more reliable. In addition, this structure allows the SRM to be powered in all four quadrants of the torque-speed plane and can operate in a very wide speed range[35].

II.18 Conclusion

This chapter has served to introduce the fundamental principles underpinning switched reluctance motors. It has covered their operational mechanics, alongside a survey of key concepts and modeling approaches pertinent to these machines. An essential element in the operation of switched reluctance motors is the close relationship between their power supply and control mechanisms. As such, this section has elucidated the supply of the SRM, focusing on the asymmetric half-bridge converter topology, recognized for its compatibility with SRM operation. However, the realization of effective control necessitates a firm understanding of the motor's model ; consequently, this model has been presented as a foundation for the subsequent development and application of suitable control strategies.

Third Chapter

CONTROL AND COMMAND OF 6/4 SRM

IV.1 Introduction

There are several control strategies for switched reluctance motors (SRMs) mentioned in the literature. The simplest method uses a basic PI controller. In this chapter, we will look at different ways to control the SRM, starting from the classic PID controller up to direct torque control (DTC). The main goal is to address the issue of torque ripple, which is considered the biggest drawback of SRMs and often prevents them from being the top choice for many applications.We will present, discuss, analyze, and compare simulation results for a 6/4 SRM using Matlab/Simulink, all focused on reducing torque ripple.

The parameters used in our SRM model are taken from published research.

IV.2 SRM Configuration

Switched reluctance motors (SRMs) come in different configurations, but here we focus on the 6/4 type. This configuration has 3 pairs of poles on the stator and 2 pairs of poles on the rotor, which is why it's also called a three-phase SRM. The SRM is powered by a three-phase asymmetric converter, where each branch includes two IGBTs and two freewheeling diodes.

During conduction periods, the IGBTs apply a positive voltage from the power source to the stator windings, allowing positive current to flow through the phase windings. In freewheeling periods, a negative voltage is applied, and the stored energy is sent back to the DC power supply through the diodes. This helps reduce the current fall time in the motor windings.

A position sensor attached to the rotor is used to accurately set the turn-on and turn-off angles for each phase. By adjusting these switching angles, we can control the shape of the developed torque waveform. The switching frequency of the IGBTs mainly depends on the hysteresis band [36].

IV.3 Operating Diagram of the 6/4 SRM Control

The rotor position is detected by a position sensor, which sends its output to the error detector. The error detector compares the reference speed with the actual speed to generate an error signal, which is then sent to the controller block. Based on this error signal, the controller sends the appropriate control signals to the converter. The speed of the motor is managed by the converter through the proper excitation of the corresponding stator windings.

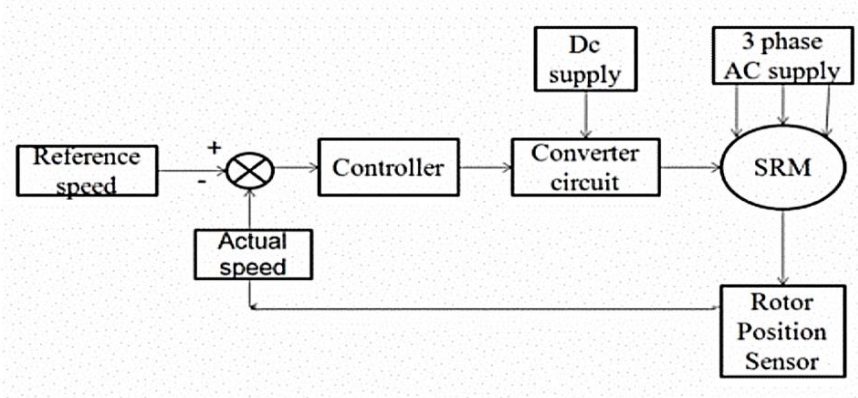


FIG IV-1: Functional diagram of an SRM control diagram [28]

IV.3.1 Simulation of the 6/4 SRM Model

A continuous supply voltage of 240 V is used. The converter's turn-on and turn-off angles are kept constant at 45° and 75°, respectively, across the speed range. The reference current is set to 200 A, and the hysteresis band is chosen as ±10 A. The SRM is started by applying a step reference at the input of the controller. The acceleration rate depends on the load characteristics. To reduce the starting time, a very light load of 5 Nm is selected.Since only the currents are controlled, the motor speed will increase according to the mechanical dynamics of the system. The SRM waveforms (phase voltages, magnetic flux, winding currents, motor torque, and speed) are displayed on the oscilloscope in Figure (3.2)

.

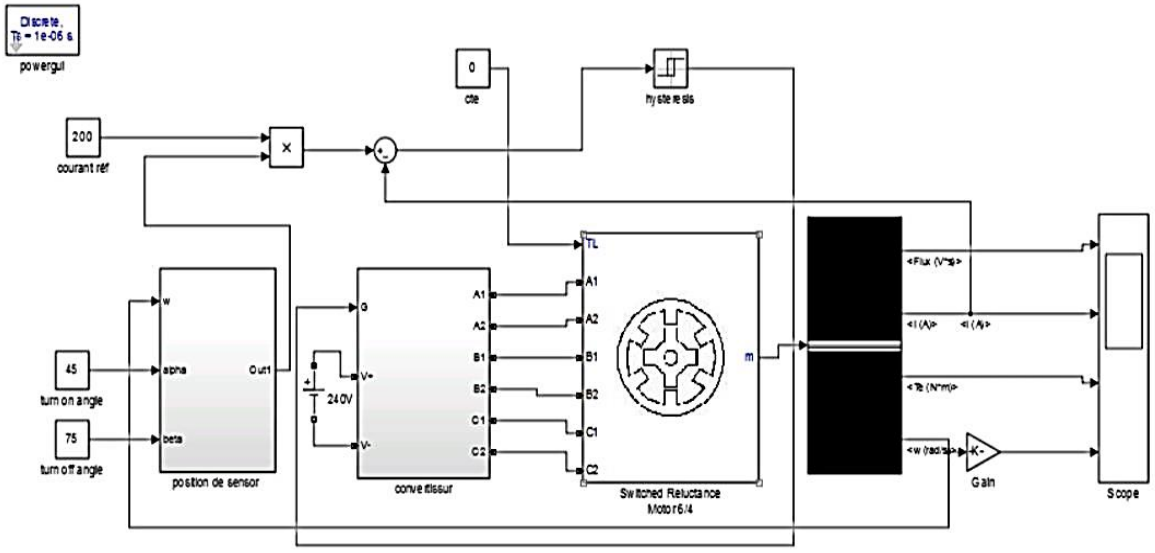


FIG IV-2: Simulation Diagram of the 6/4 SRM

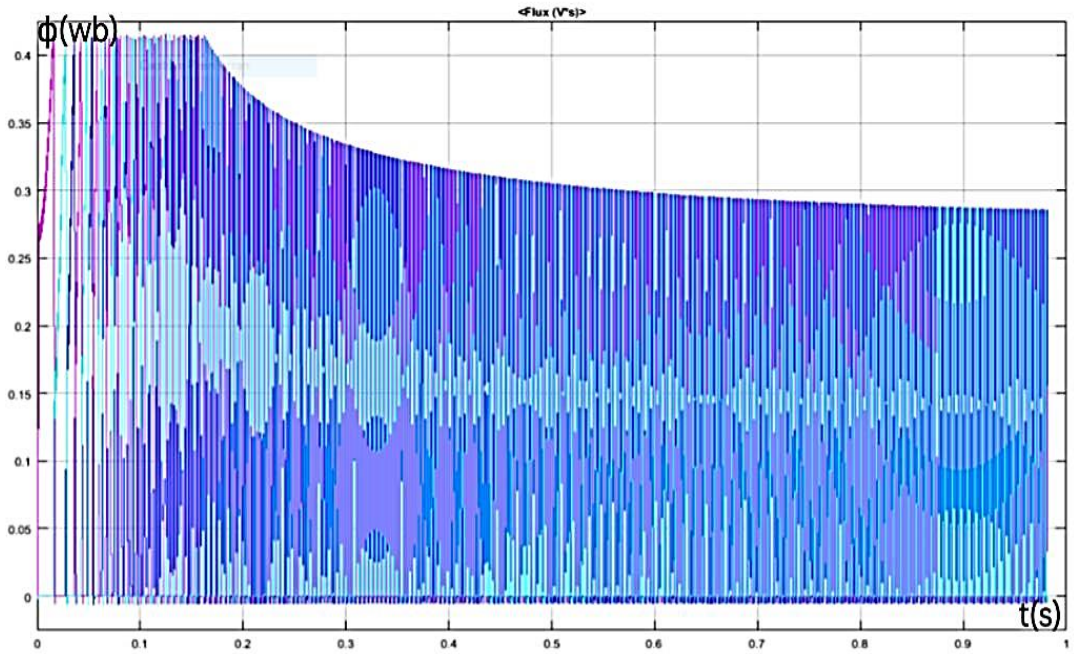


FIG IV-3: Simulation result of flux as a function of time.

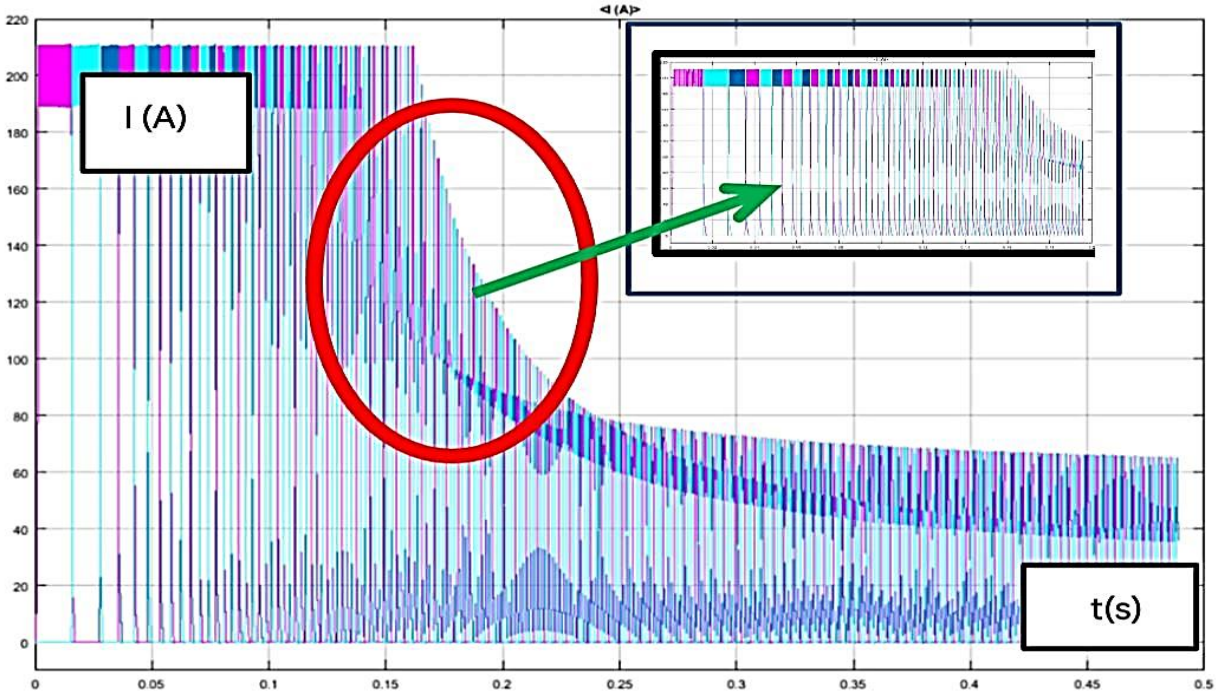


FIG IV-4: Simulation result of current as a function of time.

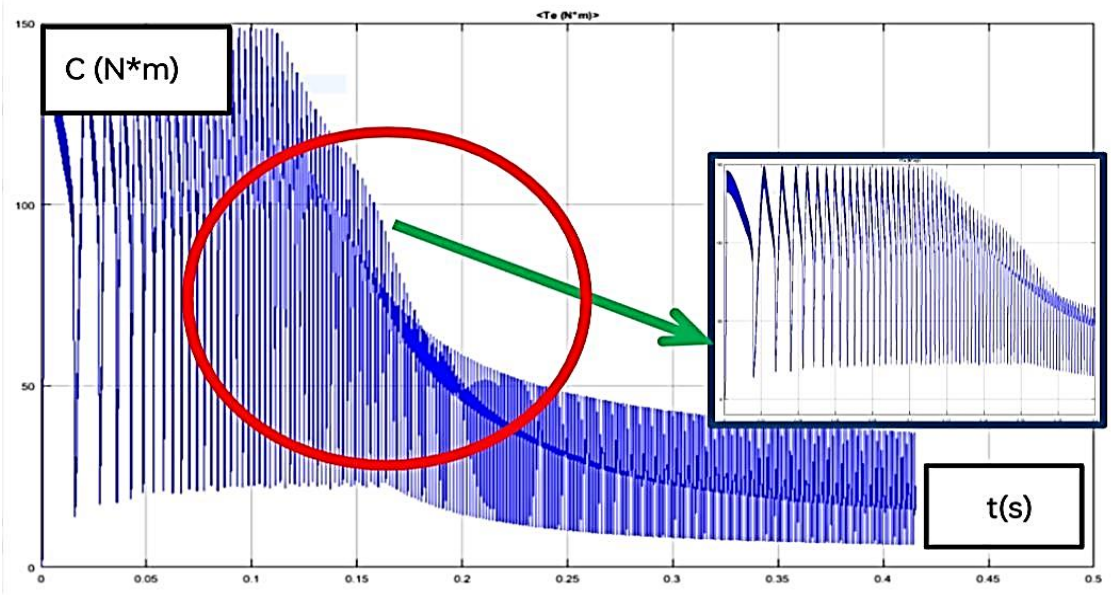


FIG IV-5: Simulation result of torque as a function of time.

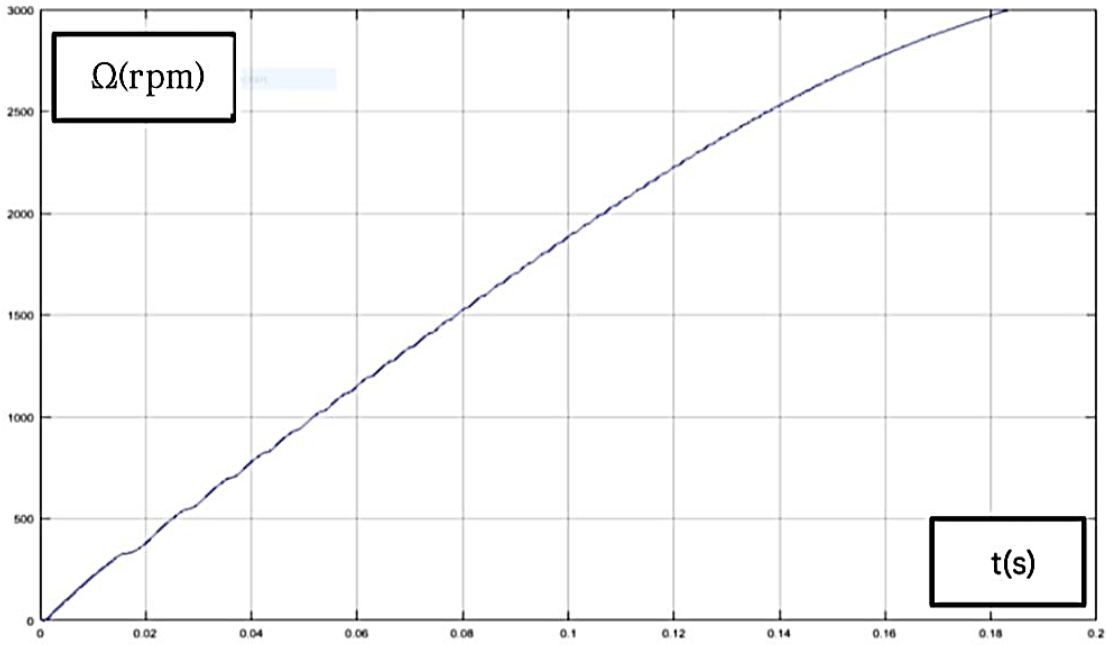


FIG IV-6: Simulation result of speed as a function of time.

The converter used in this setup is an asymmetric bridge converter. It controls the current delivered to each phase based on the rotor's position.

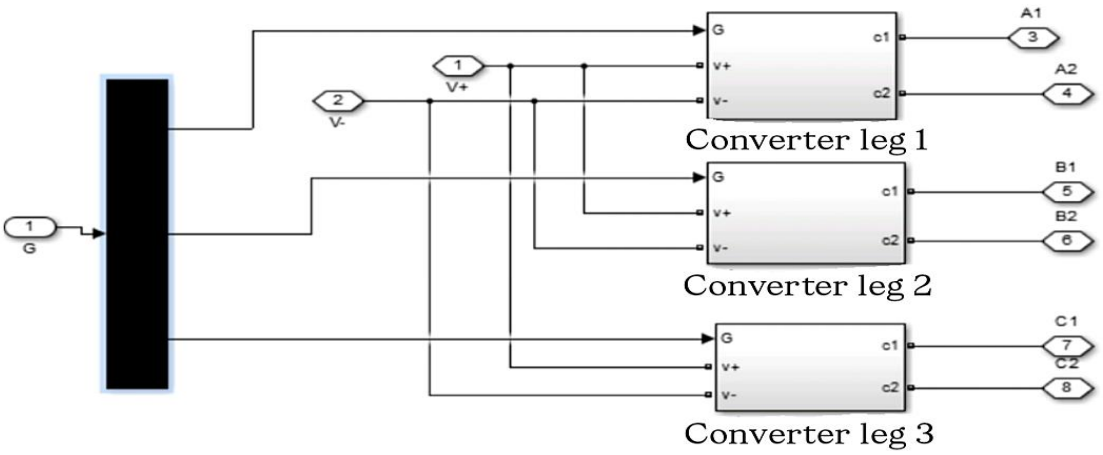


FIG IV-7: Converter block diagram

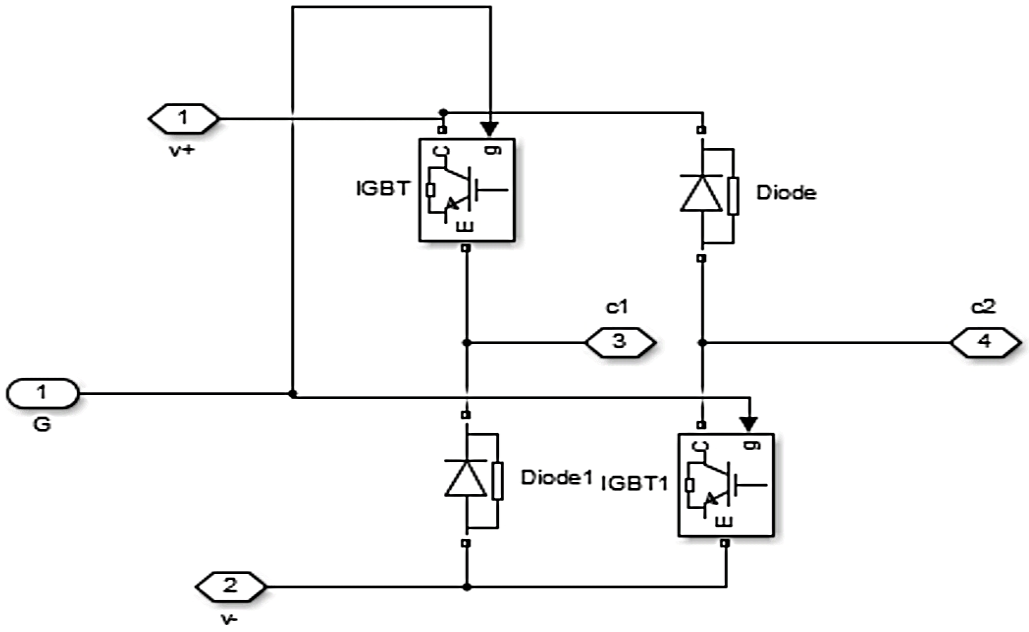


FIG IV-8: Block diagram of the converter leg

IV.4 Problem Statement

The switched reluctance motor (SRM) is known for having very high torque ripple. This is mainly due to the sequential feeding of the phases and the salient pole structure of the rotor. Because of the strong nonlinearity of the system, a simple PI controller will not be very effective. For this reason, the use of Direct Torque Control (DTC) has been chosen, as it appears

to be well suited for operating SRMs, However, to clearly demonstrate the improvement brought by DTC, a comparison with the simple PI control is necessary.

Another solution to reduce torque ripple involves using the Internal Permanent Magnet Synchronous Reluctance Motor (IPMSynRM), which is widely used in modern electric vehicle industries (such as the Tesla Model S3). However, this option is very expensive due to the use of permanent magnets made from rare earth materials. This alternative will be briefly discussed in this work, with the expectation of a more detailed investigation in the future.[37]

IV.5 Converter Control by Hysteresis

To maintain a constant torque output from the machine, a second technique is employed. This technique relie on supplying the SRM with predetermined currents based on motor characteristics, following a trapezoidal torque reference that ensures constant torque over a full electrical cycle.This method is often implemented using hysteresis current controllers. These controllers work by enforcing a current reference within a hysteresis band, thus effectively controlling the phase currents and maintaining the desired torque.

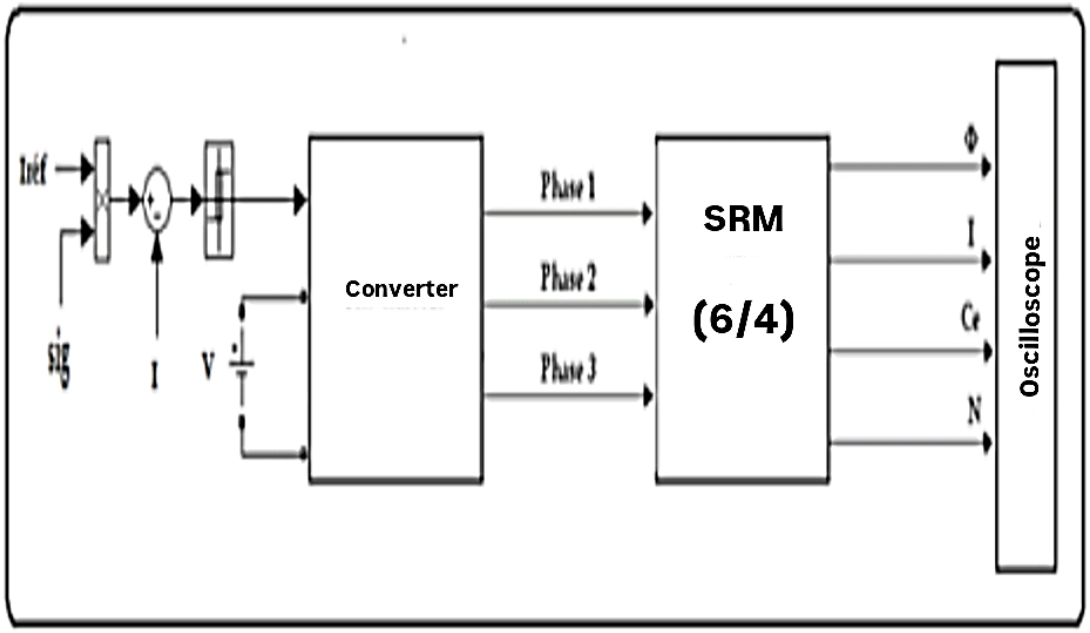


FIG IV-9: Hysteresis control diagram of the converter [29]

IV.5.1 Hysteresis Control Principle

The principle of this control method relies on controlling the converter switches to limit the current variation in the motor phase within a predefined band around the current reference. The

switching instants of the converter switches are determined by instantaneously comparing the actual current to the reference band. The comparator output is connected to the converter's control logic to enforce switching of the devices whenever the current deviates from the hysteresis tolerance of its reference [38].

IV.6 Speed Regulation Using a PI Controller

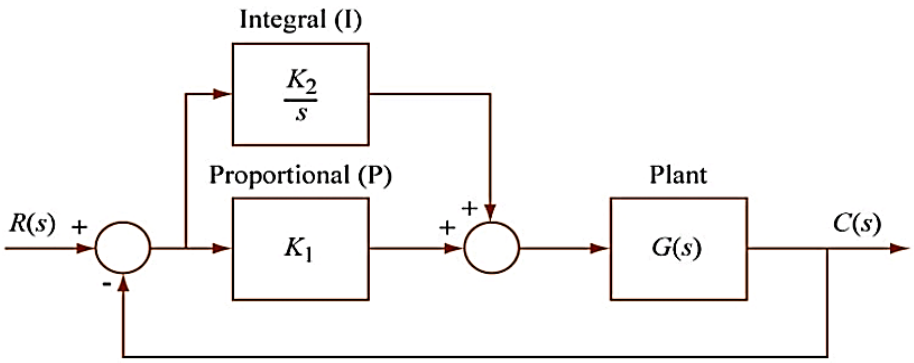


FIG IV-10: Block diagram of a PI controller [30]

IV.6.1 Conventional PI Control Method

The PI controller is commonly used in industrial drive systems. In many industrial processes, speed control is essential, particularly during transient events, to ensure product quality. Multiple nonlinearities are involved in drive systems.

For switched reluctance motors (SRMs), the PI controllers used in cascaded speed régulations loops generate a command signal defined by :

$$\mathbf{U = Kp\ e(t) + Ki \int e(t)dt} \qquad (\mathbf{3.1})$$

Where:

- **e(t)** : The error representing the difference between the setpoint value and the measured value of the controlled variable.
- **Kp** and **Ki** : The proportional and integral gains.

The calculation of the gains for the speed loop of the SRM uses the mechanicequation of SRM which is :

$$\mathbf{Te = J\frac{d\Omega}{dt} + fr\Omega + TL} \qquad (\mathbf{3.2})$$

The parameters of the PI speed controller are calculated assuming that the current loops' dynamics are negligible compared to the speed loop dynamics. This is due to the very small electrical time constant compared to the mechanical time constant. The command signal for the speed controller represents the total reference torque of the machine Te' :

$$\mathbf{Te' = Kp(\Omega' - \Omega) + \ Ki\int (\Omega' - \Omega)dt} \qquad (3.3)$$

Where:

- **(Ω'-Ω)** : Error between the setpoint speed and the measured speed in a closed-loop Te'=Te, We can write :

$$\mathbf{J\frac{d\Omega}{dt} + f\Omega + TL = Kp(\Omega' - \Omega) + \ Ki\int (\Omega' - \Omega)dt} \qquad (3.4)$$

The equation is derived:

$$\mathbf{J\frac{d^2\Omega}{dt} + (fr + Kp)\frac{d\Omega}{dt} + Ki\Omega = Ki\Omega`} \qquad (3.5)$$

Via state-space modelling:

$$\mathbf{G(p) = \frac{G(p)}{L(p)}} \qquad (3.6)$$

$$\begin{pmatrix} \mathbf{X' = Ax + Bu} \\ \mathbf{Y = Cx + DU.} \end{pmatrix} (3.7)$$

And :

$$\boldsymbol{u = \Omega' \ et \ y = \Omega}$$

it's assumed that :

$$\begin{cases} \mathbf{x_1 = y = \Omega x_1' = y = x_2.} \\ \mathbf{x_2 = y = \frac{d\Omega}{dt} x_2' = y'' = x_3} \end{cases} \qquad (3.8)$$



With u=Ω' and y=Ωwe find :

$$\mathbf{A} = \begin{bmatrix} 0 & 1 \\ -\frac{K}{J} & -\frac{fr}{J} + \frac{Kp}{J}, \end{bmatrix} \quad \mathbf{B} = \frac{0}{\frac{Ki}{J}}, \ \mathbf{C} = [1 \quad 0] \begin{bmatrix} \ \end{bmatrix}$$

By substituting the matrices A, B, and C with their expressions into the equation, we obtain :

$$G(s) = \frac{\frac{Ki}{j}}{s^2+\left(\frac{fr}{j}+\frac{Kp}{j}\right)s+\frac{Ki}{j}} \quad (3.9)$$

The closed-loop transfer function's denominator is modeled using a standard second-order system format.

$$s^2 + \left(\frac{fr}{j} + \frac{Kp}{j}\right)s + \frac{Ki}{j} = s^2+2\omega_n\xi_{s+}\omega_n^2 \quad (3.10)$$

So we can define PI settings with :

$$K_P = 2J\omega_n\xi_s + f_r$$

$$K_i = J\omega_n^{2.} \quad (3.11)$$

To obtain a closed-loop speed response with optimal performance, the speed controller incorporates anti-windup compensation. The PI speed controller's structure, including its gains, is illustrated in the accompanying diagram.

Simulation of the MRV6/4 under Matlab Simulink can be performed using a basic PI controller for speed regulation and indirect torque control, as depicted in the figure. The asymmetric converter topology is employed here, with the single-phase converter configuration and PI parameters displayed in the figure.

IV.6.2 Determination of KP, Ki

The command signal is always proportional to the error signal and the proportional gain KP using a proportional controller. This will also reduce the rise time and error but will never eliminate the error. The integral control will reduce the error, in principle, to a zero value, while derivative control is used to anticipate the future behavior of the error signal by using corrective actions based on the rate of change of the error signal.

Derivative control will increase the system's stability, reduce overshoot, and improve transient response. Derivative control action can never be used alone because this action is only effective during transient periods. The PI controller allows a control loop to respond faster with

less overshoot and is the most popular control method with a wide margin. The combined action presents the advantages of each of the three individual control actions [28].

The stator resistance is 0.05 ohms and the motor inertia is 0.05 kg/m². The values of the controller constants KP, Ki, and depend on the system to be controlled, so after proper tuning and tests for the best conditions, the values of the constants used for this analysis were obtained as illustrated in Figure (3-11).

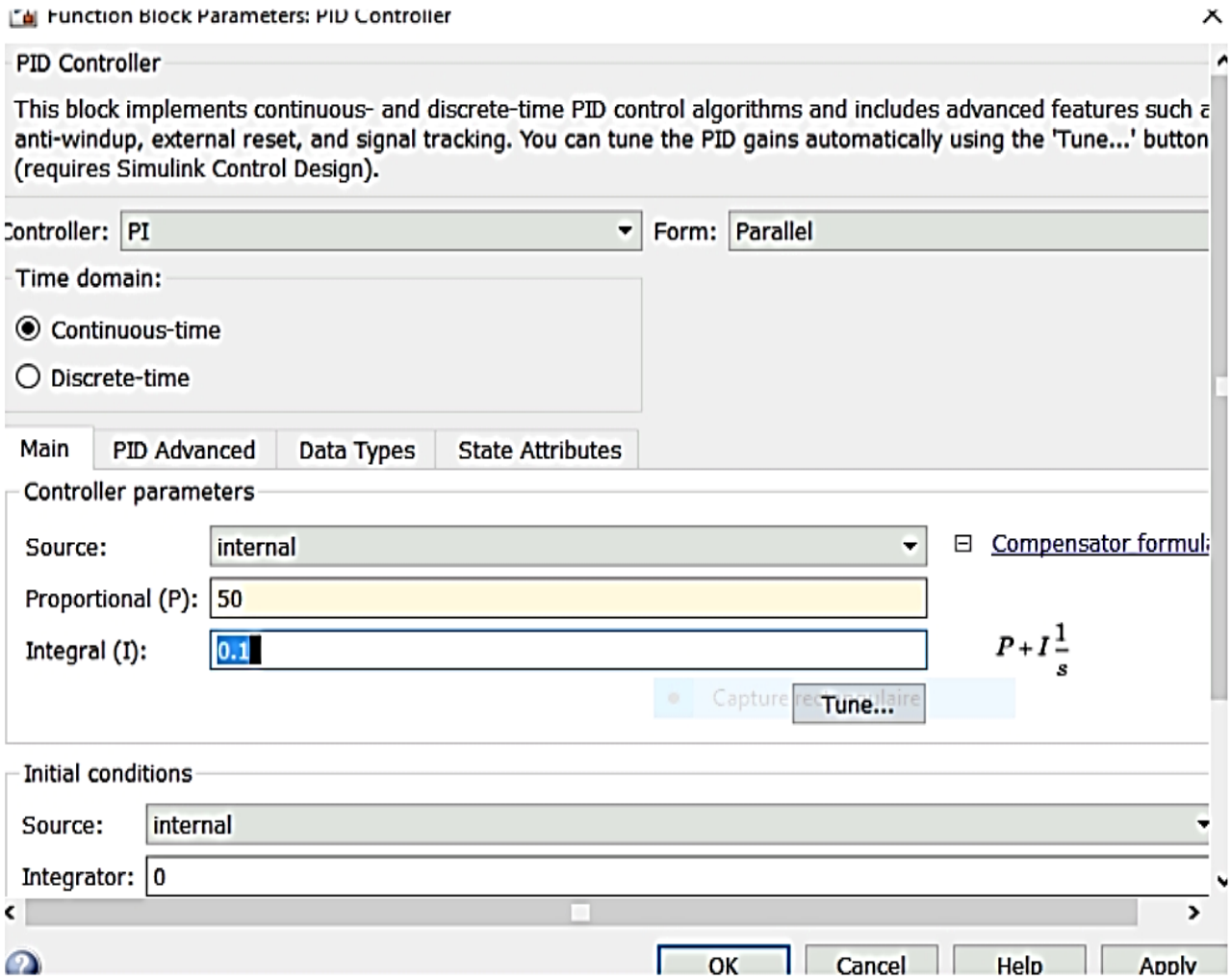


FIG IV-11: The parameters of the PI controller

The reference speed was set to 1,000 rpm, 2,000 rpm, and 3,000 rpm, and the resulting response was displayed on the oscilloscope. The graph shown on the oscilloscope represents speed versus time. As the reference speed increases, the trace shows that the settling time increases. The oscilloscope indicates that with the PI controller, there is a speed overshoot and oscillation before stabilizing at the reference value. This overshoot remains with the PI

controller even after proper tuning. The settling time is shorter with the PI controller, and the steady-state error is eliminated. The simulation was also extended to a load condition of 5 Nm. The overall results are presented in the table.

IV.6.3 Result of simulation

- Ω=1000 rpm
- TL=0

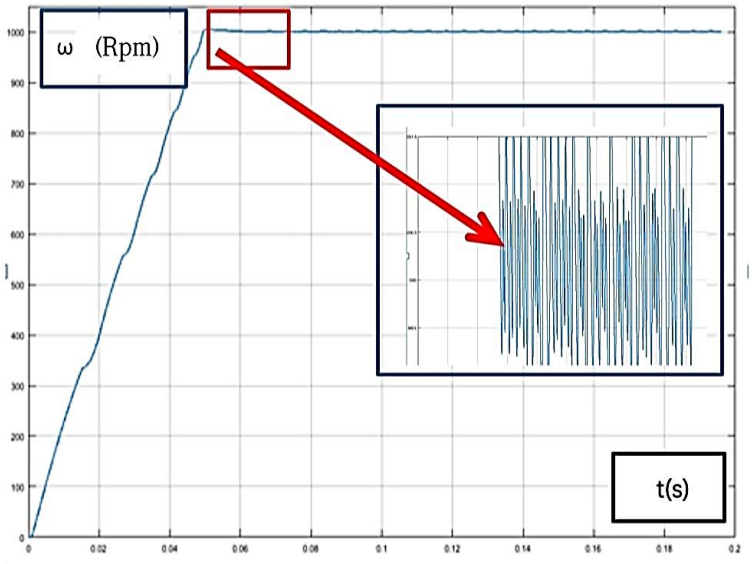


FIG IV-12: Simulation result at 1000 rpm speed without load

- TL=5Nm

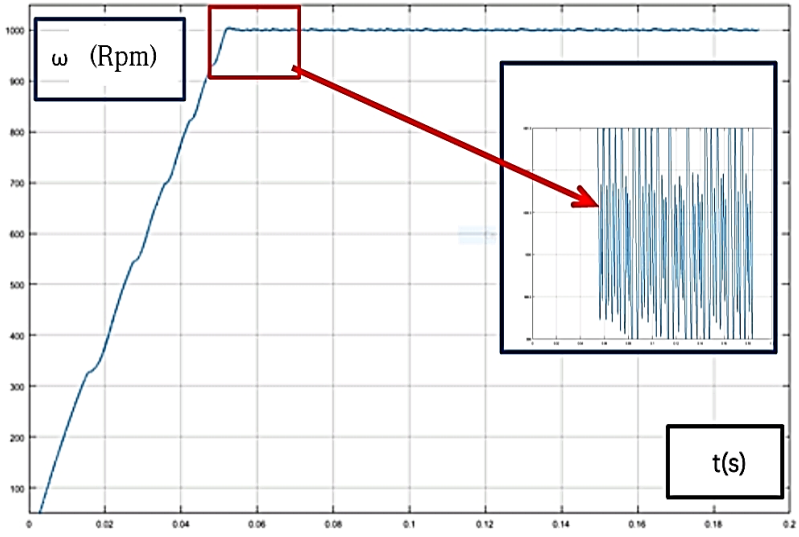


FIG IV-13: Simulation result at 1000 rpm speed with load

- TL=0Nm
- Ω =2000 rpm

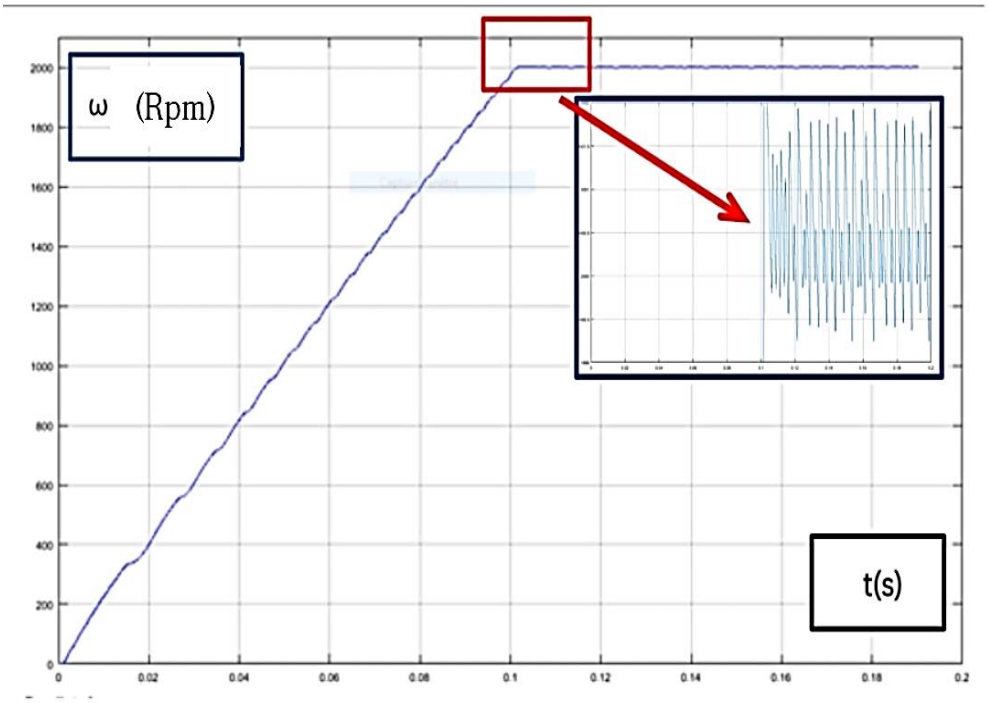


FIG IV-14: Simulation result at 2000 rpm speed without load

- TL =5Nm

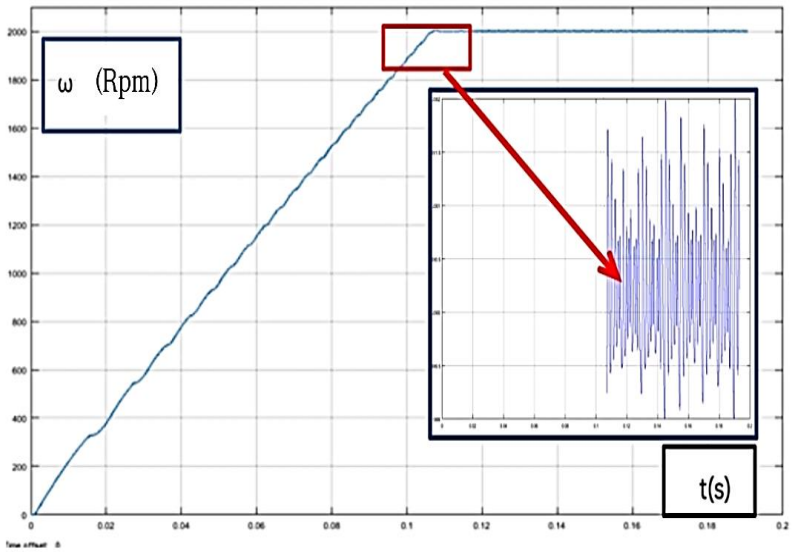


FIG IV-15: Simulation result at 2000 rpm speed with load

- Ω=3000 rpm
- TL=0Nm

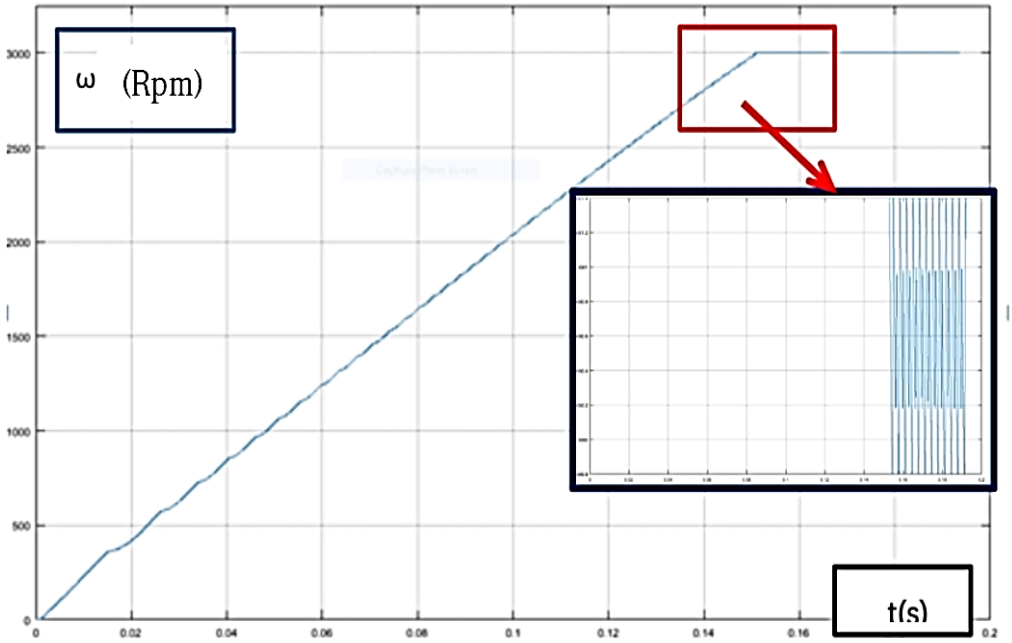


FIG IV-16: Simulation result at 3000 rpm speed without load

- TL= 5Nm

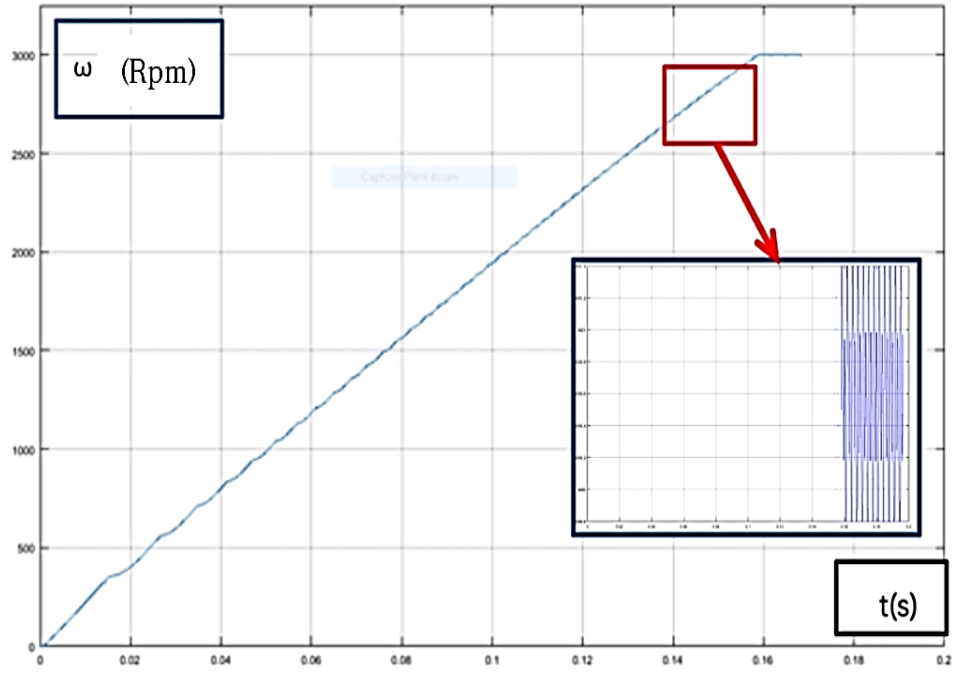


FIG IV-17: Simulation result at 3000 rpm speed withload

Table IV-1: Settling time of the speed with and without load

Speed (Rpm)	Settling time Ts(sec) no load	Response time Ts(sec) TL=5Nm
1000	0.063	0.058
2000	0.106	0.108
3000	0.156	0.161

The PI controller has a low settling time and low overshoot, making it the most suitable for speed control under load conditions. The reduction in settling time becomes more pronounced when the speed reaches 50,000 rpm or higher. Thus, this study demonstrates the superiority of the PI controller, reflected by the elimination of speed overshoot, removal of steady-state error, and reduction of settling time when the motor speed transitions from zero to the reference speed.

The 6/4 switched reluctance motor (SRM) is driven by an asymmetrical bridge converter, and its construction and control are simpler compared to a commutated motor. The SRM was modeled and simulated in Simulink to achieve optimal performance. The PI controller delivered the best results in terms of reducing settling time, eliminating speed overshoot, and removing steady-state error.

IV.7 Generation of Vibrations and Noise in the SRM Integrated into EVs

Electric vehicles (EVs) have developed very rapidly in recent years due to the need to reduce energy consumption and pollutant emissions from conventional vehicles. Considerable efforts have been made in the research and development of batteries, electric motors, and power electronics. The switched reluctance motor (SRM), with its advantages, is one of the motors that provides great satisfaction when used in EV propulsion. The problem of vibrations and noise in these motors remains a major drawback.

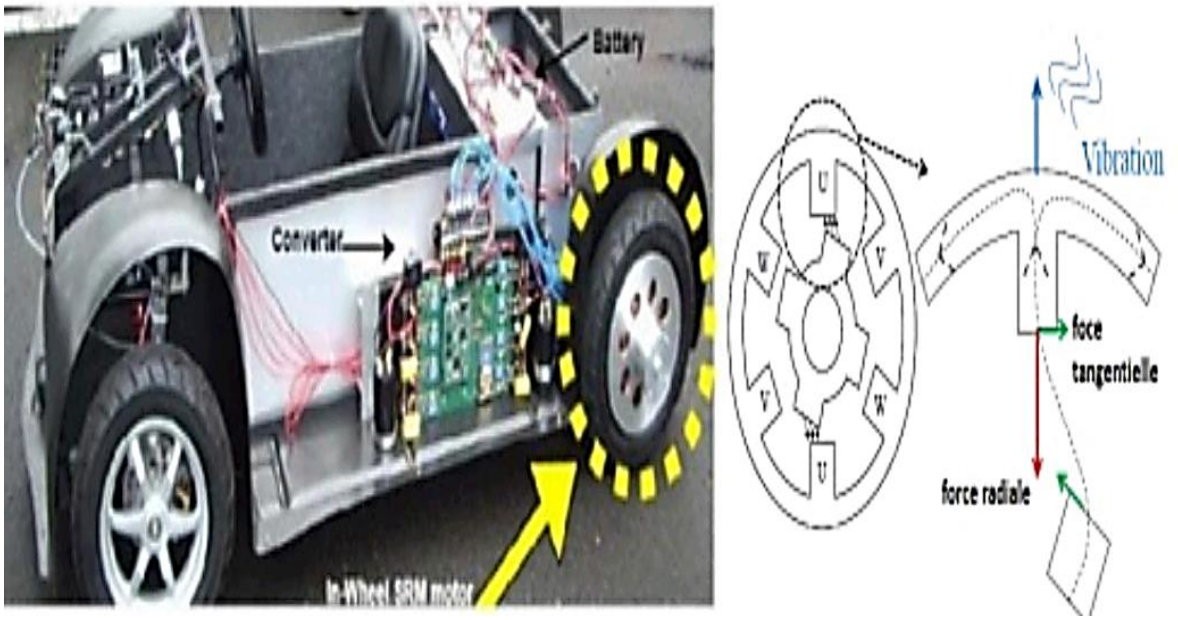


FIG IV-18:SRM, forces and vibrations [18]

Once the phase is energized, a magnetic flux circulates in the magnetic circuit. This flux generates an attractive force between the stator and rotor teeth. This force is decomposed into two components : a tangential component that produces torque, and a radial component, which is useless and considered the main source of vibrations and noise in the switched reluctance motor (SRM).

This radial force is generally ten times greater than the tangential force. It causes displacements of the structure in the radial direction. This phenomenon can be worsened if one or more frequencies of this force coincide with a natural frequency of the structure [18].

IV.7.1 Torque ripples

The torque ripple produced in a switched reluctance motor (SRM) is considered one of its main drawbacks. This mainly occurs due to the sequential switching of the motor phases and changes in the air gap length. In the SRM, the fundamental control challenge is to produce torque without ripple. The presence of torque ripple leads to undesirable noise and vibrations during operation. The static characteristics as well as the magnetization model of the individual phases determine the amount of torque ripple during operation.

IV.8 First Solution

IV.8.1 Direct Torque Control (DTC)

Over the past decades, technological advances in power electronics and industrial computing have enabled the development of advanced control strategies for electric machines. To position

our study within the field of DTC, a state-of-the-art overview of DTC is presented by gathering key publications relevant to our research.DTC was proposed by Takahashi [TakI89] in the mid-1980s. Compared to vector control, DTC is less sensitive to machine parameter variations and provides precise and fast torque dynamics. The principle of this control method is to directly control the machine's torque and stator flux. In this framework, two hysteresis comparators are used to compare estimated values with references, then the inverter states are directly controlled through a predefined switching table.

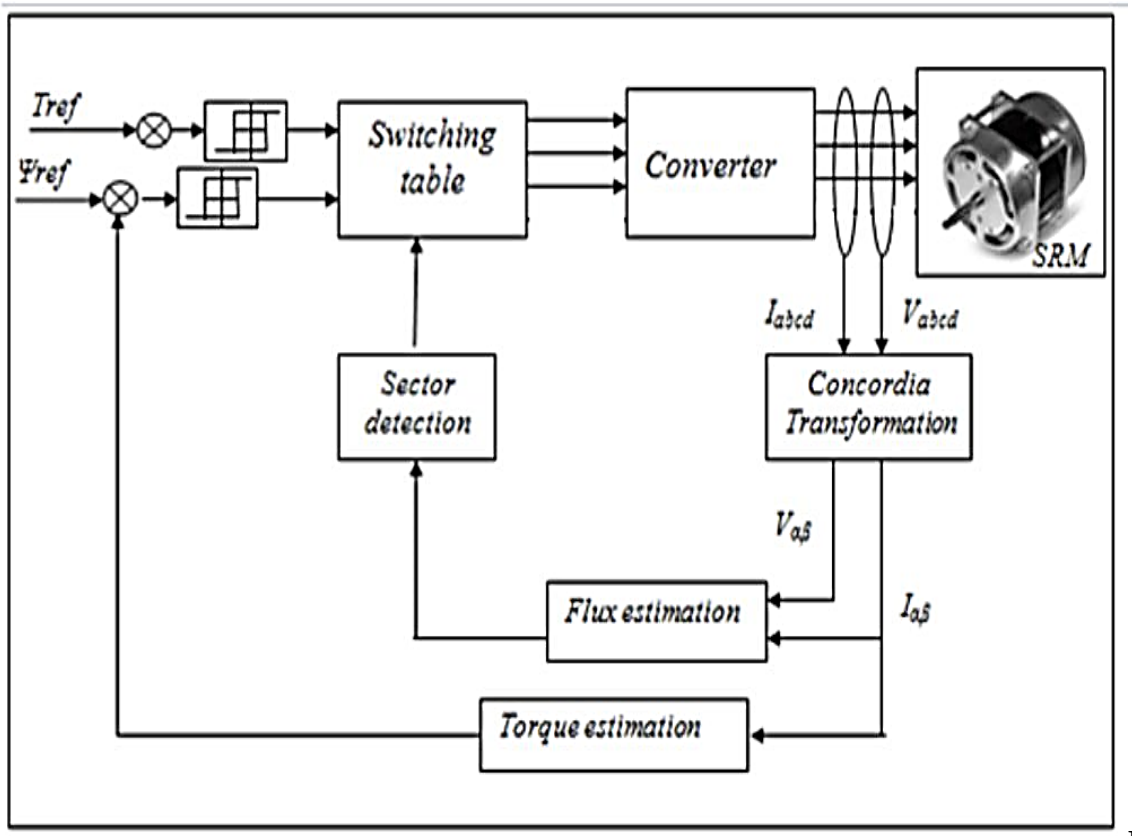


FIG IV-19: Diagram of the basic structure of DTC.

The DTC strategy for the asynchronous machine includes the main components of the DTC control structure with speed regulation as follows :

- Two estimators for torque and stator flux based on the stator model,
- A switching table for the desired stator voltage vector, designed according to the flux and torque error signals.
- Two hysteresis comparators : one with two levels for flux control, and the other with three levels for electromagnetic torque control [39].

IV.8.2 Control of Stator Flux and Electromagnetic Torque

The power flux equation can be written as follows :

$$\mathbf{vi^2 = Ri^2 + i\frac{\partial\varphi(\theta,i)}{\partial i}\frac{di}{dt} + i\frac{\partial\varphi(\theta,i)}{\partial\varphi}\frac{d\varphi}{dt}} \qquad \mathbf{(4.3)}$$

The effective power flux Peff of the electrical source can be defined as follows :

- **Peff = ei** **(4.4)**
- **e = (v – Ri)** **(4.5)**

In a differential time interval dt , the differential electrical energy dWe transferred from the source is given by :

$$\mathbf{dW_e = eidt} \qquad \mathbf{(4.6)}$$

The energy equation to find an expression for motor torque production is written as :

$$\mathbf{dW_e = dW_m + dW_f.} \qquad \mathbf{(4.7)}$$

Where :

- dW_m and dW_f : are respectively the differential mechanical energy and the field energy. The field energy can be separated into its constituent components as shown in the equation.

$$\mathbf{dWf = \frac{\partial Wf}{\partial i}\,di\Big|\theta = cos\,tan\,t + \frac{\partial Wf}{\partial\theta}\,d\theta\Big|i} \qquad \mathbf{(4.8)}$$

From the consideration of the stored field energy, it can be shown that :

- $\mathbf{dW_e = i\frac{\partial\varphi(\theta,i)}{\partial i}di|\theta}$ **(4.9)**
- $\mathbf{dWf|\theta = cos\,tan\,t = i\frac{\partial\varphi(\theta,i)}{\partial i}di|\theta}$ **(4.10)**

By substituting equation (4.6) into equation (4.7), we can observe that :

$$\mathbf{dWm = i\frac{\partial\varphi(\theta,i)}{\partial i}d\theta - \frac{\partial Wf}{\partial\theta}d\theta} \qquad \mathbf{(4.11)}$$

The instantaneoustorque is defined by :

$$\mathbf{T = \frac{dWm}{d\theta}} \qquad \mathbf{(4.12)}$$

Thus, by substituting equation (3.41) into equation (3.40), the expression for the instantaneous torque production of an SRM phase can be written as :

$$\mathbf{T = i\frac{\partial\varphi(\theta,i)}{\partial\theta} - \frac{\partial Wf}{\partial\theta}} \qquad \mathbf{(4.13)}$$

$\frac{\partial Wf}{\partial\theta}$ Is negligible. Therefore, using this approximation, the following equation for torque production can be derived as follows:

$$\mathbf{T = i\frac{\partial\varphi(\theta,i)}{\partial\theta}} \qquad \textbf{(4.14)}$$

IV.8.2.1 Principle of Direct Torque Control Applied to the SRM

The introduction of direct torque control is based on the orientation of the stator flux, and by considering that $Vs>>R_sI_s$, when a voltage vector is applied for a certain period of time, we obtain :

$$\mathbf{\Delta\varphi = \varphi_{s2} - \varphi_{s1} = V_s.\Delta t} \qquad \textbf{(5.1)}$$

This equation implies that the tip of the stator flux vector (t) φs moves along a straight line whose direction is given by the applied voltage vector Vs

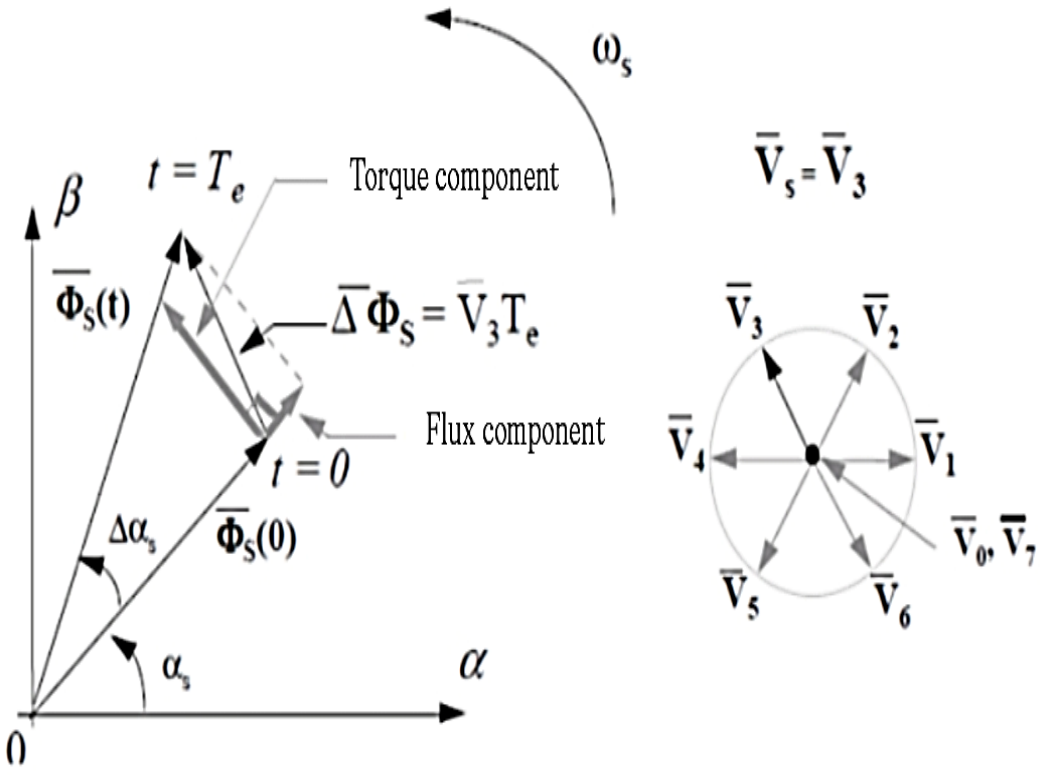


FIG IV-20: Evolution of the tip **φ**s(t) for negligible RsIs [32]

The radial component (of the flux) of the voltage vector changes the amplitude of φs, and the tangential component changes the position of the flux and thus the torque value.

By choosing an appropriate sequence of voltage vectors Vs over constant time periods Ts, it is therefore possible to operate with a practically constant flux magnitudeφs, making the tip

ofφsfollow a trajectory given by the derivative$\frac{d\varphi}{dt}$, which corresponds to the speed of movement of the tip of φs When neglecting the termRs Is, the voltage is given by the term **Vs=** $\frac{\mathbf{d\varphi}}{\mathbf{dt}}$.

The rotation speed ofφs Depends on the choice ofVs ; it is maximal when the vector Vsis perpendicular to the direction ofφs, zero if a zero vector is applied, and can also be negative[40].

IV.8.3 Building the Switching Table

However, unlike DTC for conventional AC machines, each phase can be in three states, resulting in a total of 27 possible configurations. Yet, to define six voltage vectors of equal amplitude, spaced by($\frac{\pi}{6}$)radians as in a classic DTC algorithm, the six possible voltage vector states are V1, …, V6, based on the sum of the voltage vectors in each phase.

At any moment, one of the six voltage states is selected to keep the stator flux and torque within a hysteresis band. As in conventional DTC, if the flux is in zone k, its magnitude can be increased by switching the voltage to vector Vk+1 or Vk-1, and can also be decreased by switching to the opposite vector [41].

Table IV-2: Selection of vectors according to the zones

N	N	V1	V2	V3	V4	V5	V6
φs = 1	Ce = 1	V2	V3	V4	V5	V6	V1
φs = 1	Ce = 0	V6	V1	V2	V3	V4	V5
φs = 0	Ce = 1	V3	V4	V5	V6	V1	V2
φs = 0	Ce = 0	V5	V6	V1	V2	V3	V4

The fluxes in the three phases are resolved onto fixed α-β axes using the three-phase transformation shown in Figure 3.11. The equation for the fluxes in the α-β axes is obtained asfollows :

$$\varphi_{s\alpha}(n)= \varphi_{s\alpha}(n-1)+[Vs\alpha(n-1)]-r_s\text{-}i_{s\alpha}(n-1)]\ T_e. \quad (5.2)$$

$$\varphi_{s\beta}(n)= \varphi_{s\beta}(n-1)+[V_{s\beta}(n-1)]-r_s i_{s\beta}(n-1)]\ T \quad (5.3)$$

The flux magnitude and its phase are calculated by :

$$\varphi s = \sqrt{\varphi a^2 + \varphi b^2} \quad (5.3) \quad (5.4)$$

$$\theta\varphi = \text{arctg}\ \frac{\varphi sb}{\varphi sa} \quad (5.5)$$

The variations of the electromagnetic torque can be controlled solely from the rotational speed of the flux vector φs. Table (III.2) shows the evolution of both flux and torque for each of the four vectors Vi+1, Vi+2, Vi−1,Vi−2 that can be applied in zone Zi.

When the flux is in zone i, the control of flux and torque can be ensured by selecting one of the following six voltage vectors:

- If Vi+2 is selected, then the amplitude of the flux φs decreases and the torque Tem increases;
- If Vi−1is selected, then the amplitude of the flux φs increases and the torque Tem decreases;
- If Vi−2 is selected, then the amplitude of the flux φs decreases and the torque Tem decreases;
- If Vi+1 is selected, then the amplitude of the flux φs increases and the torque Tem increases.

Table IV-3: Selection of voltage vector

Vector. Vi	Vi−2	Vi−1	Vi+1	Vi+2
Φs	↓F	↑F	↑F	↓F
Te	↓Te	↓Te	↑Te	↑Te

IV.8.4 Simulation of SRM Control Results with DTC

The performance of the 6/4 SRM is applied to a load (Cr = 1.5 Nm at t = 0.07 s). The speed, torque, and flux follow their references with robust and very fast dynamics, without exceeding the hysteresis bands, resulting in a circular flux trajectory.

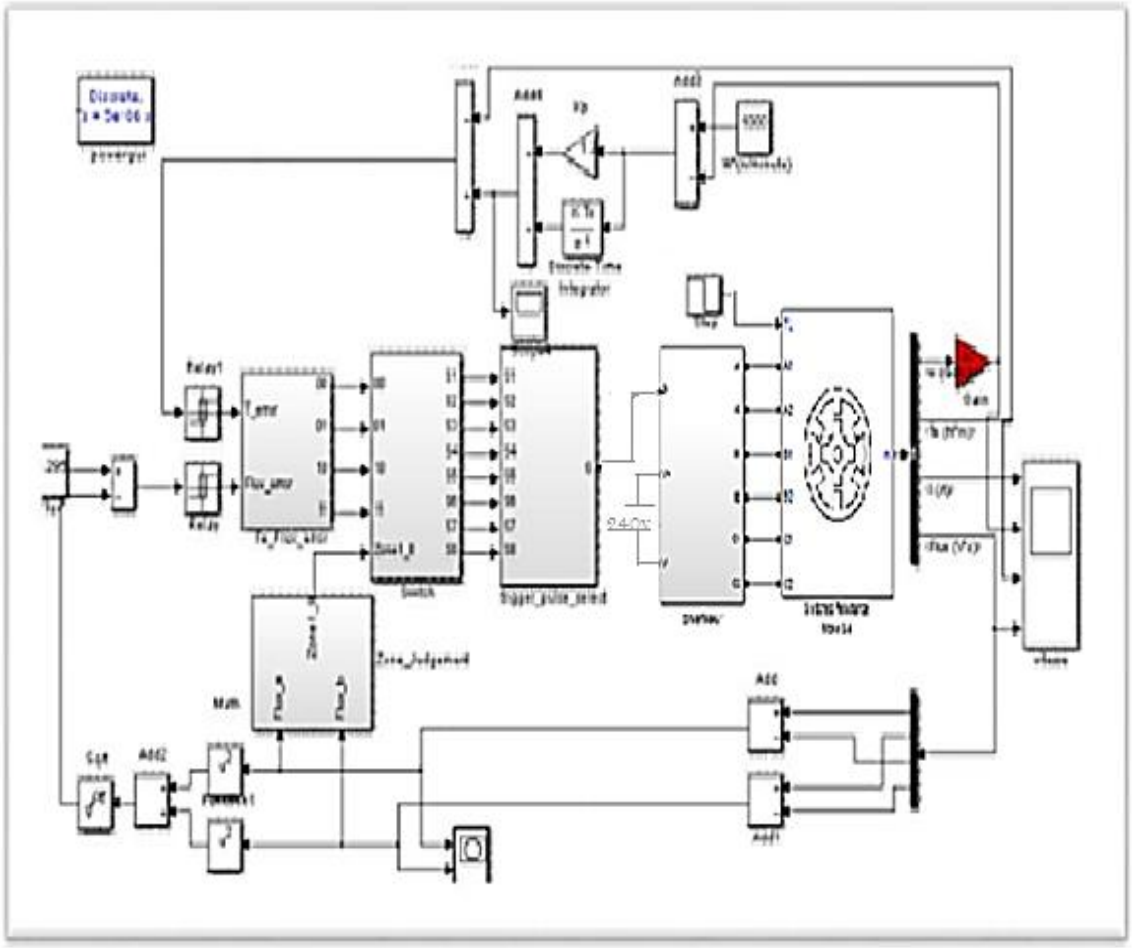


FIG IV-21: DTC block diagram

IV.8.5 Simulation result

- with DTC:

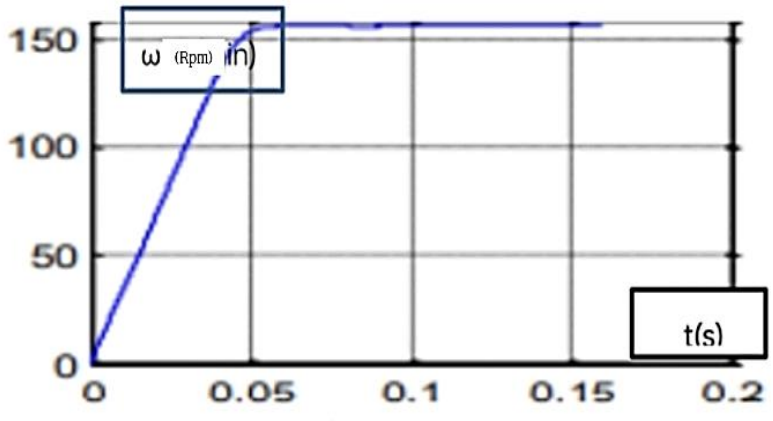


FIG IV-22: Simulation result of the speed of SRM6/4 with DTC

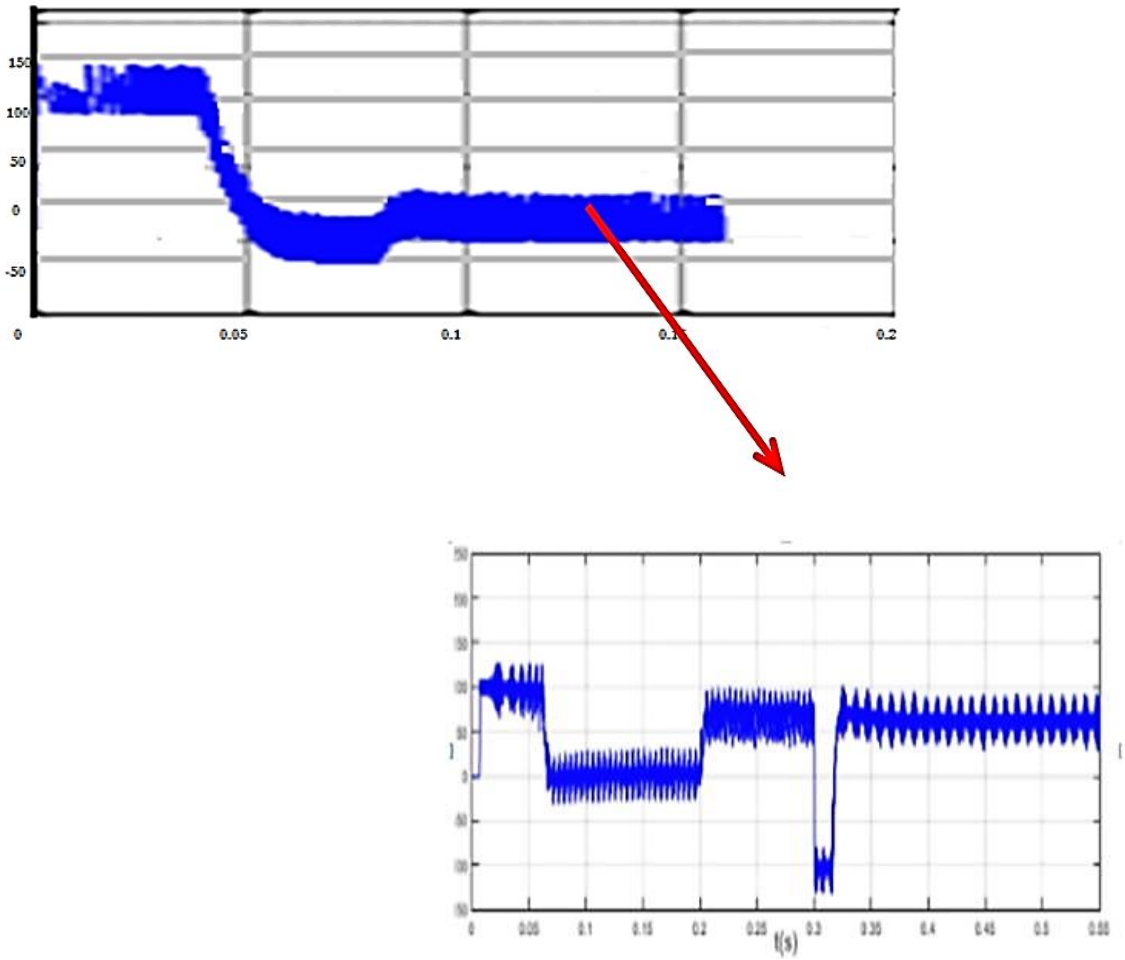


FIG IV-23: Simulation result of the speed of SRM6/4 with DTC

- With control :

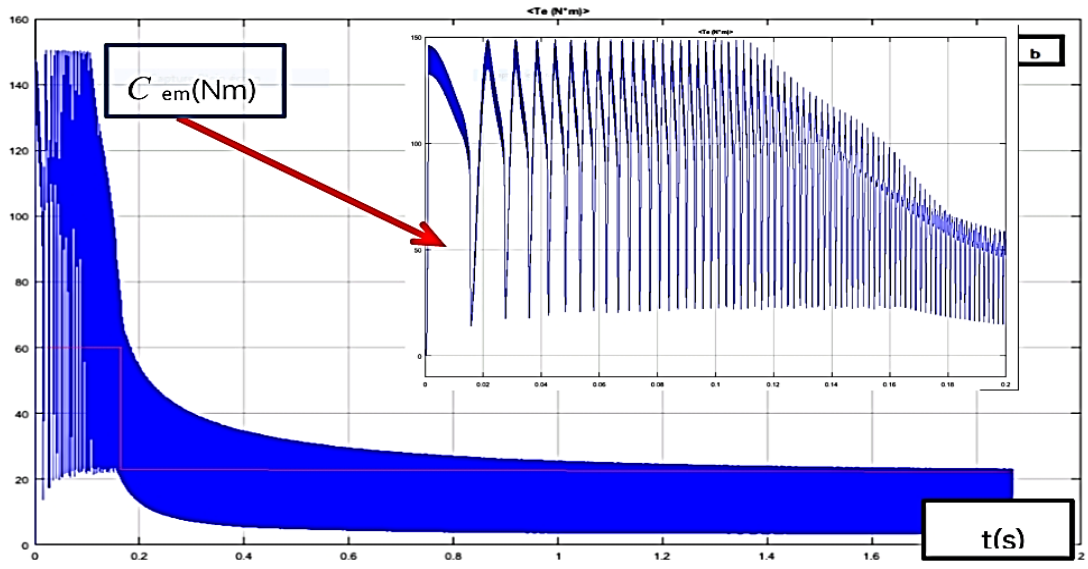


FIG IV-24: Torque simulation with DTC

➢ With PI :

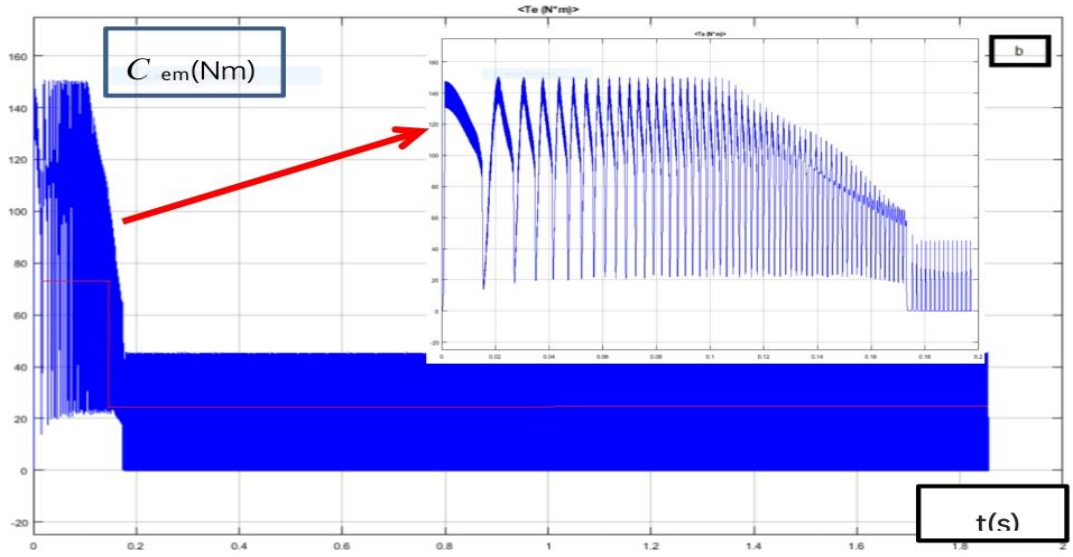


FIG IV-25: Torque simulation with PI controller

- **Interpretation**

From the results, we notice that the torque ripples have decreased compared to the results obtained without control and with a simple PI controller. Thanks to direct torque control (DTC), we were able to improve the machine's performance.

IV.9 Second Solution to Reduce Torque Ripples

Tesla Motor engineers made a remarkable design choice when developing the Tesla Model 3. They abandoned the conventional, proven induction motors and replaced them with a new type of motor called the IPMSynRM (Interior Permanent Magnet Synchronous Reluctance Motor). These motors have a completely different design, using both magnetic action and reluctance action.

Tesla Motors has also started replacing the induction motors in their Model S and X with this new motor. Tesla uses IPMSynRM motors in both RWD and AWD cars for better efficiency[42]

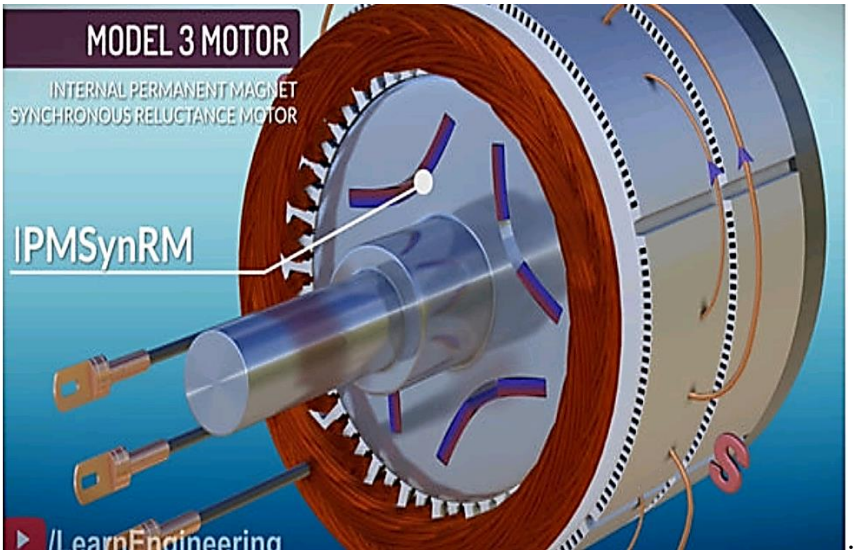


FIG IV-26:IPMSynRM[35]

IV.9.1 Tesla Model 3 IPM-SynRM

The IPMSynRM is a combination of permanent magnet motors and SynRM motors, where permanent magnets are placed in the slots of the SynRM motor, deep inside the iron core. To understand this simply, we will first explain the two types of motors, starting with the permanent magnet motor.

IV.9.1.1 Permanent Magnet Motor

Permanent magnet (PM) motors operate based on the attraction between two magnetic fields. They produce good starting torque from the same motor volume. This is more efficient when used with a controller, as they do not suffer energy losses in the rotor. However, PM motors have a problem : when the car runs at high speed, permanent magnet motors perform poorly due to the generation of back electromotive force (back-EMF) in the stator coils.



FIG IV-27: PM motors operate based on the attraction between two magnetic fields[36]



FIG IV-28: A permanent magnet produces a combined magnetic field[36]

The back electromotive force (back-EMF) is induced when the magnetic field lines produced by the permanent magnets cut through the stator windings. It is clearly a voltage opposing the supply voltage of the stator. The higher the rotor speed, the greater the back-EMF generated.

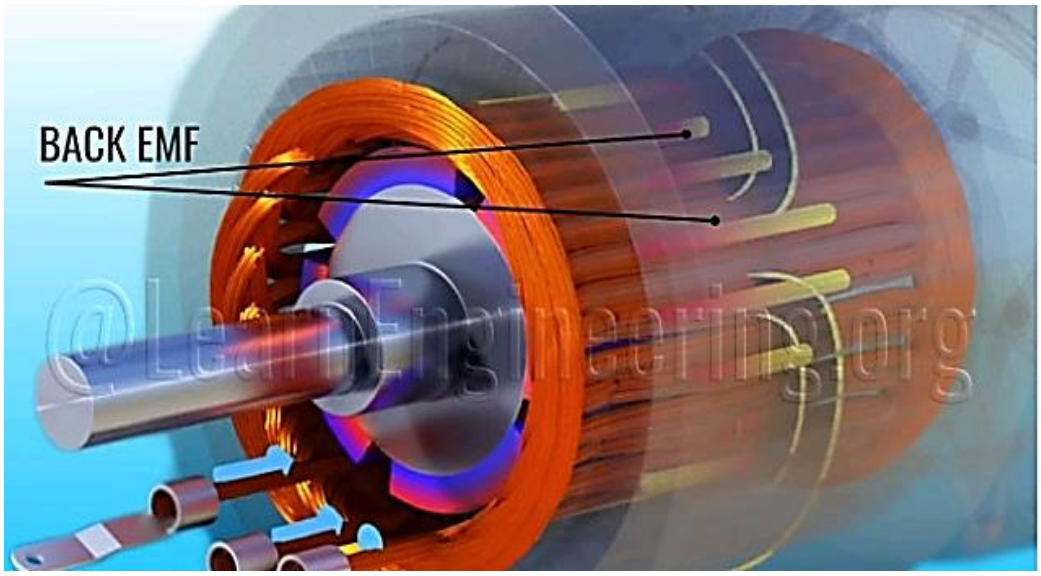


FIG IV-29: The back electromotive force is induced when the magnetic field lines produced by the permanent magnets are linked to the stator windings[36]

Another disadvantage is that the magnets cause magnetic eddy current losses, which increase the heat in the machine and are unfavorable. Keep this explanation in mind ; now we will explain the second type of motor.

IV.9.1.2 SynRM

We will now understand how Tesla's motor overcomes these problems by using SynRM motors. For high-speed operation, Tesla engineers used the reluctance property of iron. Here, iron opposes magnetic fields less than air does. Using this phenomenon, SynRM motors generate rotation. To achieve this rotational movement, slots are cut into the rotor. At this rotor position, the rotor is in a high reluctance state, as shown in Fig.3-31 on the left side of the image. However, if the rotor is rotated by 45 degrees, it faces very low reluctance.

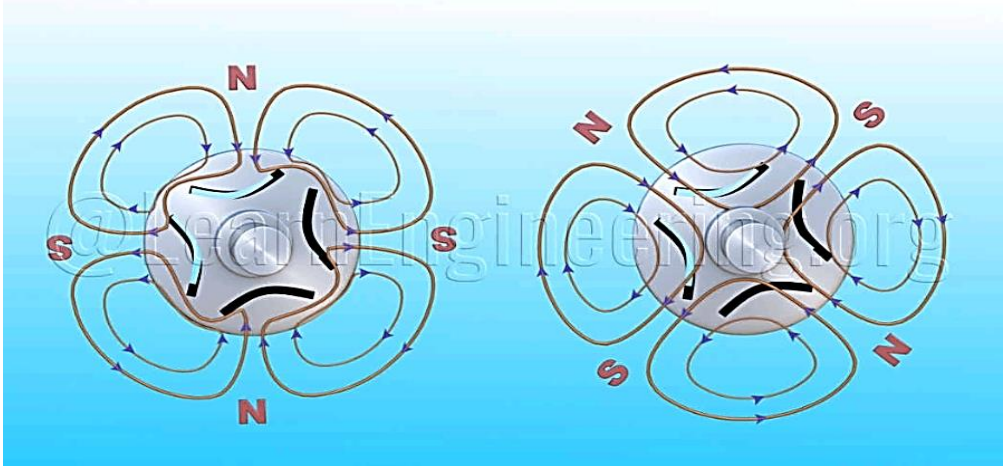


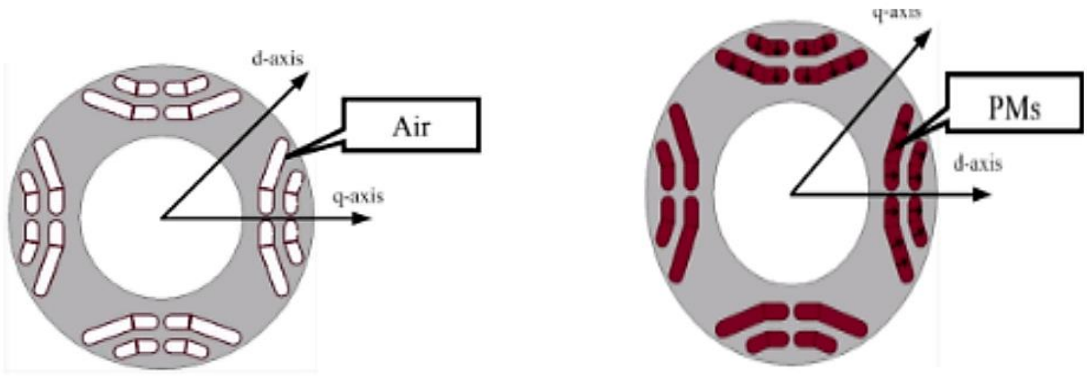
FIG IV-30: The rotor is in a high reluctance state[36]

The rotor always tends to reach a low reluctance state. Therefore, if the magnetic field rotates, the rotor will turn with it so that the rotor can always be in a low reluctance state. The rotor's rotational speed will be the same as the RMF (Rotating Magnetic Field) speed. The torque produced by this phenomenon is called « reluctance motor torque, » and these motors are called synchronous reluctance motors.

You must keep in mind that SynRMs can improve high-speed operation, they do not have back-EMF problems, and permanent magnet motors can be designed to operate properly at low speed.

In this case, it is good to integrate SynRM technology into the permanent magnet motor. If we do so, these motors can operate efficiently.

An interesting choice about this design is that the permanent magnet and reluctance parts of this motor behave completely differently concerning the RMF position.



Internal Permanent Magnet (IPM) Motor Synchronous Reluctance Motor (SynRM)

FIG IV-31:IPM motor and SynRM motor [35]

IV.10 Torque Analysis of the IPMSynRM Motor

Now, let's analyze the Tesla Model 3 motor. It is clear from the total torque graph that when the RMF angle is around 50 degrees, as shown in Figure 8 below, the motor produces its maximum torque. Tesla Motors engineers ensured that when you start the car, the RMF angle is about 50 degrees, guaranteeing maximum torque production by using both reluctance and permanent magnet torque.However, after reaching a certain high speed, back electromotive force (back-EMF) appears. To overcome this, field weakening is applied, which I will briefly explain below [42].

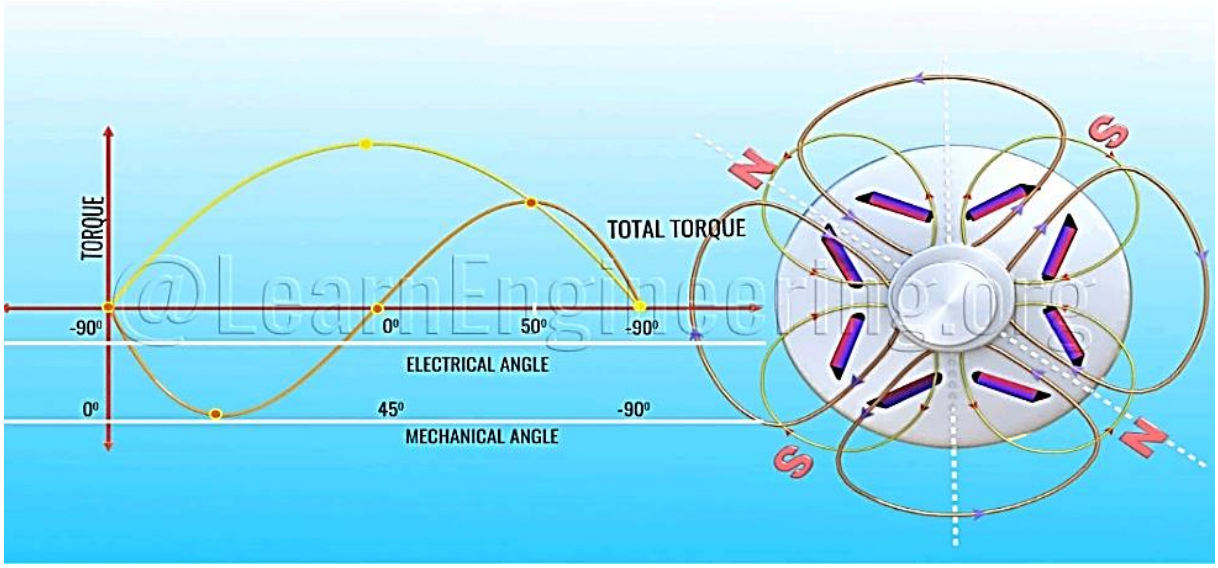


FIG IV-32:Graph of the RMF angle, approximately 50 degrees [36]

The permanent magnets of the IPMSynRM motor still have some effect on the stator, producing a back electromotive force (back-EMF) at higher speeds. To solve this problem, we

can align the RMF opposite to the permanent magnetic field, as shown in Figure 9 below on the left.

The RMF weakens or almost cancels the permanent magnet field, as shown in Figure 9 below on the right. In this way, even at high speeds, these motors will not produce much back-EMF. Obviously, at this stage, the torque production will mainly come from the reluctance effect [42].

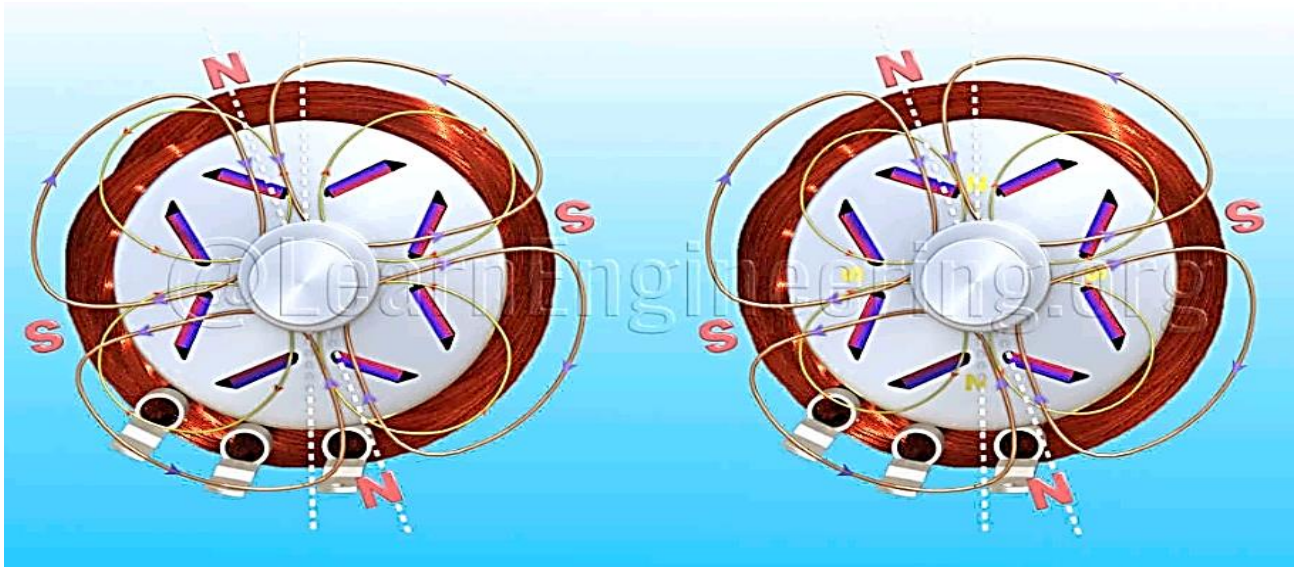


FIG IV-33: Field weakening [36]

IV.11 Conclusion

In the first part of this chapter, we carried out a simulation of the 6/4 switched reluctance machine without any control and observed significant torque ripple, which reduced the performance of the SRM.

Based on these results, we implemented a PI controller to improve speed. To further enhance machine performance, we developed the second part using DTC control to minimize torque ripple. The results show that torque ripples decreased and the DTC drive performance of the SRM was analyzed with the appropriate selection of six spatial voltage vectors for both constant and variable load torque. Torque and flux were maintained within their respective hysteresis bands.

In the final part of the chapter, we proposed a new type of motor combining two types, IPM and SynRM, which further helps reduce the level of these ripples. We can conclude that with the PI regulator and DTC controller, the machine's performance has been significantly improved.

General Conclusion

Our work contributes to the control and regulation of switched reluctance motors (SRMs) for their use as traction motors in electric vehicles.

A state-of-the-art review of electric vehicles was presented, and the core components of EV traction systems were discussed, focusing on available technologies. We chose the switched reluctance motor due to its numerous advantages, making it competitive against other motor types, and its frequent selection for modern electric vehicles owing to its strong performance.

However, the SRM has one prohibitive drawback: torque ripples, which cause significant vibrations and acoustic noise.

This work involves modeling, control, regulation, and simulation of a switched reluctance motor, starting with uncontrolled power supply, then a simple classical control (PI). These two approaches proved insufficient due to the SRM's highly nonlinear behavior caused by its salient rotor structure and the sequential power supply of the asymmetric converter.

To better meet reference requirements and minimize torque ripples, we proposed direct torque control (DTC) for a 6/4-pole three-phase SRM. Simulation results showed a remarkable reduction in ripples and significantly improved SRM performance.

Our work is divided into three chapters:

- **First Chapter:**
  Focused on the need to adopt new techniques to reduce fossil fuel consumption. We discussed electric vehicles, their state of the art, operation, and key factors favoring SRMs as traction motors for EVs.
- **Second Chapter:**
  Covered the fundamentals of switched reluctance machines, their modeling, and operating principles. We highlighted the optimization of SRM control as a current research topic.
- **Third Chapter:**
  Addressed control of the 6/4-pole SRM. To solve torque ripple issues, we proposed:
  A classical PI speed controller.
  Direct torque control (DTC), based on directly determining switching sequences for voltage inverter switches.

A second solution: the IPMSynRM motor, a modern but costlier alternative to eliminate ripples without complex control.

For future work, we suggest deeper exploration of IPMSynRM technology and experimental validation of the results if possible

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